2007 Boston Harbor benthic monitoring report

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2007 Boston Harbor Benthic Monitoring Report

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EXECUTIVE SUMMARY

The direct discharge of waste products into Boston Harbor for several decades had a profound impact on the sedimentary environment of Boston Harbor, including degradation of the communities of organisms found associated with the sediments. In 1985, in response to both the EPA mandate to institute secondary treatment and a Federal Court order to improve the condition of Boston Harbor, the newly created Massachusetts Water Resources Authority (MWRA) instituted a multifaceted approach to upgrading the sewage treatment system, including an upgrade in the treatment facility itself and construction of a new outfall pipe to carry the treated effluent to a diffuser system located 9.5 mi offshore in Massachusetts Bay.

Surficial sediments are critical to many ecosystem functions because the flow of energy (organic carbon, living biomass, secondary production) and nutrients (nitrogen, phosphorus) are regulated by processes at the sediment-water interface. Characterization of the benthic environment from both physical and biological points of view has therefore been a key part of the MWRA's long-term sediment monitoring within Boston Harbor. Sampling is conducted using both traditional grab sampling for infaunal benthos and reconnaissance with the sediment profile imaging (SPI) camera as a means of obtaining *in situ* data on the dynamics of seafloor processes and biogenic activity.

Monitoring began in September 1991 and was conducted twice a year, in April and August, to track changes in the sediments and infaunal communities at eight grab stations and 60 SPI stations throughout the harbor. In 2003, sampling was reduced to once a year (August), and, in 2004, an additional station was added in the inner harbor near a Combined Sewer Overflow (CSO). All stations were reoccupied in August 2007.

2007 Results

In 2007, Boston Harbor continued to show signs of improved benthic habitat quality for infauna. The cline of relative habitat quality in Boston Harbor, based on the patterns of association between the sediment, infauna, and SPI variables, from lower habitat quality at station T04 in Dorchester Bay to higher habitat quality at T08 in the outer harbor was still present in 2007.

The presence of microalgal mats in the Charles River, near the old Nut Island outfall, and in Dorchester and Quincy Bays may be an indication that areas further away from the harbor mouth are starting to show signs of improved benthic habitat quality. However, most of the stations in Dorchester and Quincy Bays appear to be characterized by anaerobic processes and carbon accumulation. In contrast, stations near the harbor mouth appeared more aerobic with little carbon accumulation.

As in 2005 and 2006, the benthic infauna at several stations was dominated by a small polychaete, *Nephtys cornuta*, although the absolute numbers appear to be declining. The population irruption of this species coincided with the decline of the large amphipod populations in 2004, and it is likely that it is fueled by the detrital remnants of the crustaceans and/or other organisms exposed by the storms in subsequent seasons, as well as the microalgal mats detected by SPI.

The occurrence, spread and retreat of *Ampelisca* tube mats at stations in the harbor has been followed closely over the course of the monitoring program. Reish and Barnard (1979) found that slight increases in organic matter resulted in increased amphipod abundance, but beyond or below a certain level, amphipod numbers decreased. Following a major peak in numbers in 2003, *Ampelisca* populations were virtually eliminated from the harbor in 2005, probably as a consequence of several severe storms that affected the benthic habitats. Only a small rebound in numbers of these amphipods was noted in 2006 and again in 2007. Other amphipod species, particularly the large-bodied *Leptocheirus pinguis*, have been found in increasing numbers at some stations.

Abundances of *Clostridium perfringens* have decreased significantly over the monitoring period at five of the harbor stations, but increased (0.2 to 10-fold) at all harbor stations in 2007 compared with 2006 values. At most harbor stations, however, the 2007 abundances were less than average values measured over the entire monitoring period. The 2007 increase may reflect natural variability, redistribution of surface sediments, or inputs to the system.

Long-term Patterns: Has the Harbor Changed?

Taylor (2005, 2006) summarized the major patterns in freshwater flows and loadings of total nitrogen (TN), total phosphorus (TP), total suspended solids (TSS), and particulate organic carbon (POC) to Boston Harbor for a 15-year period between 1991 and 2005. He elucidated four periods, which were related to the timing of improvements to the wastewater treatment in the harbor: Period I, prior to December 1991, Period II from the end of sludge dumping in December 1991 through mid-1998, Period III, from mid-1998 to September 2000, and Period IV, which began in September 2000 with the transfer of the discharge to the new offshore outfall.

Benthic community parameters for the harbor overall were summarized for Taylor (2006) time periods, offset by one year to allow for any lag time in the response of benthic populations to decreased pollutant loads (Table 1). Periods II and III appear the most similar for all parameters. Fisher's *alpha* shows a steady increase through all time periods, whereas the mean values of other parameters appear identical or decline between subsequent periods (*e.g*., number of species, periods II and III; Shannon diversity, periods III and IV), reflecting the increase and decline of amphipod populations, and, in the last two or three years, the irruption of *Nephtys cornuta*.

Given the physical and oceanographic attributes of the study area (*i.e.*, a near-coastal environment that is relatively shallow compared with offshore areas, and a continuing pollutant load, albeit reduced, from CSOs or other industrial sources), it is probable that the harbor benthos will continue to evidence episodic irruptions and declines of populations of amphipods and other species as has been documented over the past several years. Even so, the concomitant decrease in carbon loading and levels of *Clostridium perfringens*, plus increase in community parameters such as species richness and Fisher's *alpha* at several locations in the harbor, point towards a cleaner and healthier benthic environment.

Table 1. Benthic community characteristics for Boston Harbor grab stations summarized by discharge periods defined by Taylor (2006).

Parameter	Period			
	I **before Dec. 1991**	**II** **Dec 1991–mid-1998**	**III** **mid-1998–Sep. 2000**	**IV** **after Sep. 2000** ***(after outfall diversion)***
Groupings offset by one year	***n*= 48** **(1991–1992)**	***n* = 144** **(1993–1998)**	***n*= 70** **(1999–2001)**	***n* = 144** **(2002–2007)**
Number of Species	25.1 ± 14.25	34.7 ± 13.6	33.5 ±14.2	40.0 ± 16.6
H′	2.11 ± 0.81	2.41 ± 0.90	2.80 ±0.78	2.73 ± 0.97
log-series *alpha*	4.14 ± 2.13	5.50 ± 2.00	6.13 ± 2.24	7.29 ± 3.09
Rarefaction curves	1991 Lowest	Low	Intermediate	Highest
Fauna	highest abundances of opportunistic species such as *Streblospio benedicti* and *Polydora cornuta*	declining abundances of opportunistic species, some amphipod species numerous	fewer opportunists, more oligochaetes, some amphipod species numerous	some species from Massachusetts Bay, rise and decline of amphipods, irruption of opportunistic polychaete *Nephtys cornuta*

1. INTRODUCTION

1.1 Background

1.1.1 History of Discharges to Boston Harbor

Boston Harbor has had a long history of anthropogenic impacts dating back at least to colonial times (Loud 1923). In addition to the damming of rivers and the filling of salt marshes and shallow embayments to create the present footprint of the city, the direct discharge of waste products has had a profound impact on the composition of the biological communities in the harbor. Prior to the 1950s, raw sewage was discharged into Boston Harbor primarily from three locations: Moon Island, Nut Island, and Deer Island. In 1952, the Nut Island treatment plant became operational and began treating sewage from the southern part of Boston's metropolitan area. The Deer Island treatment plant was completed in 1968, thus providing treatment for sewage from the northern part of the area. (The third location, Moon Island, was relegated to emergency status at that time and not used routinely thereafter.) The effluent was discharged continuously from both plants; an annual average of 120 million gallons per day (MGD) from Nut Island and 240 MGD from Deer Island. Storm events caused up to 3.8 billion gallons per year (BGY) of additional material to be occasionally discharged to the harbor through the system of combined sewer overflows (CSOs) (Rex *et al.* 2002).

Sludge, which was separated from the effluent, was digested anaerobically prior to discharge. Digested sludge from Nut Island was pumped across Quincy Bay and discharged through an outfall near Long Island on the southeastern side of President Roads. Sludge from Deer Island was discharged through that plant’s effluent outfalls on the northern side of President Roads. Sludge discharges were timed to coincide with the outgoing tide, under the assumption that the tide would carry the discharges out of the harbor and away offshore. Unfortunately, studies have shown that the material from Nut Island often was trapped near the tip of Long Island and carried back into the harbor on incoming tides (McDowell *et al*. 1991).

In 1972, the Federal Clean Water Act (CWA) mandated secondary treatment for all sewage discharges to coastal waters, but an amendment allowed communities to apply for waivers from this requirement. The metropolitan Boston area’s application for such a waiver was denied by the US Environmental Protection Agency (EPA), partly on the basis of the observed degradation of the benthic communities in Boston Harbor. In 1985, in response to both the EPA mandate to institute secondary treatment and a Federal Court order to improve the condition of Boston Harbor, the Massachusetts Water Resources Authority (MWRA) was created. The MWRA instituted a multifaceted approach to upgrading the sewage treatment system, including an upgrade in the treatment facility itself and construction of a new outfall pipe to carry the treated effluent to a diffuser system in Massachusetts Bay located 9.5 mi offshore in deep water.

In 1989, discharge of more than 10,000 gallons per day of floatable pollutants comprising grease, oil, and plastics from the Deer Island and Nut Island treatment plants was ended. Sludge discharge ceased in December 1991, marking the end of one of the most significant inputs of pollutants to Boston Harbor. In 1995, a new primary treatment plant at Deer Island was completed, increasing the system's overall capacity and the effectiveness of the treatment. In August 1997, the first phase of secondary treatment was completed, increasing the level of solids removal to 80%. For the first time, the MWRA's discharge met the requirements of the CWA (Rex *et al.* 2002).

In July 1998, a new screening facility at Nut Island became operational, with sand, gravel, and large objects being removed from the wastewater flow prior to transport via tunnel to Deer Island for further processing. In October 1998, the old Nut Island plant was officially decommissioned, ending more than

100 years of wastewater discharges to the shallow waters of Quincy Bay. By 2000, the average effluent solids loading to the harbor had decreased to less than 35 tons per day (TPD), reduced from the 138 TPD discharged through the 1980s. On September 6, 2000, all wastewater discharges were diverted to the new outfall in Massachusetts Bay, and in early 2001, the final battery of secondary treatment became operational.

Ongoing MWRA pollution abatement projects for Boston Harbor involve reducing the number and discharge volumes from Combined Sewer Overflows (CSOs). In 1988, 88 CSOs discharged a total of about 3.3 billion gallons per year (BGY). By 1998, 23 CSOs had been closed, and pumping improvements reduced discharges to about 1 BGY, of which about 58% is screened and disinfected. By 2008, ongoing projects will reduce the number of CSO outfalls to fewer than 50, with an estimated discharge of 0.4 BGY, of which 95% will be treated by screening and disinfection (Rex *et al.* 2002).

Taylor (2005, 2006) summarized the major patterns in freshwater flows and loadings of total nitrogen (TN), total phosphorus (TP), total suspended solids (TSS), and particulate organic carbon (POC) to Boston Harbor between 1995 and 2005. He found four major periods of pollutant loadings:

- Period I was prior to December 1991. Freshwater inflows, which came primarily from area rivers, and loadings of all four fractions were elevated, principally because of discharges from the sewage treatment facilities.

- Period II was from December 1991 (end of sludge dumping) through mid-1998. During this time, discharges into the harbor were released from both the Nut Island and Deer Island facilities. Freshwater inflows and loadings of TN and TP, averaged for the entire 6.5-year period, were not significantly different from Period I. Average TSS and POC loadings, however, were significantly lower than during Period I, due to the end of sludge dumping and because of increased removal of TSS and POC from the effluent stream following improved primary treatment and upgrade to secondary treatment at Deer Island.

- Period III began in mid-1998, after the April transfer of Nut Island wastes to Deer Island for treatment and discharge, and lasted until September 2000. Freshwater flows were not significantly lower than during Periods I and II, but loadings of TSS and POC, and to a lesser extent TN and TP, did decrease significantly. For all four variables, the decreases were primarily the result of the transfer of the Nut Island discharges to the mouth of the harbor, and increased secondary treatment of the now-combined Deer Island and Nut Island flows at Deer Island.

- Period IV began in September 2000 with the transfer of the discharge offshore. For this 5-year period, average freshwater inflows and loadings of TN, TP, TSS, and POC were all significantly lower than during all three of the previous periods.

The changes in wastewater discharge from 1991 to 2005 resulted in an 80–95% decrease in loadings to Boston Harbor. Annual average loadings of TSS and POC showed a progressive decrease, starting in 1991/1992 and proceeding through 2001, after which the average loadings remained low and similar between years. For TN and TP, loadings showed some decrease with the end of sludge discharge, but remained elevated through 1998, when Nut Island flows were discharged closer to the mouth of the harbor, resulting in decreased inputs to the harbor. TN and TP showed additional, larger decreases with the transfer of the effluent discharge offshore in 2000.

1.1.2 Benthic Studies in Boston Harbor

The first extensive studies of the infaunal benthos of Boston Harbor were conducted in the summers of 1978, 1979, and 1982 in support of the secondary treatment waiver application (Maciolek 1978, 1980; McGrath *et al.* 1982). These studies documented spatial and temporal variability in infaunal communities in Boston Harbor prior to any pollution abatement projects, and informed the design of the current monitoring program.

As MWRA's long-term sediment monitoring was being developed, reconnaissance surveys were carried out using sediment profile imaging in 1989 and 1990 (SAIC 1990). This technique provides information on the depth of the apparent redox potential discontinuity (RPD), an estimation of sediment grain-size composition, the successional stage of the infauna, and the presence of any biogenic features such as burrows and tubes (Rhoads and Germano 1986). The sediment profile stations provided the means to assess benthic conditions over most of the outer Boston Harbor and Dorchester, Quincy, Hingham, and Hull Bays.

Quantitative infaunal sampling was initiated in 1991and was intended to characterize the infauna of Boston Harbor so that changes following the various phases of the Boston Harbor Project (*e.g*., sludge abatement) could be documented. Eight stations (one was later relocated) were positioned near the major effluent and sludge discharges and in key reference locations. Benthic infaunal communities and correlated sediment parameters were first sampled in September 1991, approximately three months prior to the cessation of sludge discharge. Post-abatement surveys were conducted in April/May and August 1992 to 2002; beginning in 2003 samples were collected only in August.

In 2004, a new station in the inner harbor, C019, was added to the benthic monitoring program. Sediment contaminants have been monitored at this site periodically since 1994 as part of an MWRA study of the effect of CSOs on sediment contamination in Dorchester Bay (Durell 1995, Lefkovitz *et al.* 1999). MWRA's system upgrades will greatly reduce the amount of CSO discharge to the Fort Point Channel and the bulk of the remaining flow will be treated; therefore, C019 was added to help identify environmental improvements that may result from these upgrades.

Reconnaissance surveys at 25–50 additional stations using sediment profile imaging have been carried out annually. Reports to the MWRA on the results of these surveys are available through their website (http://www.mwra.state.ma.us/harbor/enquad/trlist.html).

1.2 Report Overview

The Boston Harbor benthic monitoring program currently includes two major components: sediment imaging (SPI) and analysis of benthic infaunal communities, complemented by the determination of sedimentary parameters. Results from the 2007 survey are presented in this report and compared with results from previous years. Recent reports (Maciolek *et al.* 2006a,b) have suggested that the infaunal community is responding to some degree to changes in the discharges to the harbor. The occurrence and spread or retreat of *Ampelisca abdita* tube mats, and the increase in species numbers and diversity at some of the stations are considered especially important.

The sampling design and field methods are presented in Chapter 2, with detailed station data in Appendix A. Sediment images are discussed in Chapter 3 and the infaunal benthic communities in Chapter 4. The sediment studies, which include grain-size analysis, total organic carbon (TOC) content determination, and quantification of the sewage tracer, *Clostridium perfringens*, are summarized in Appendix B. The raw data generated for all of these components are available from the MWRA; summaries are included in the appendices to this report.

2. 2007 HARBOR FIELD OPERATIONS

by Stacy A. Doner

2.1 Sampling Design

The station array provides spatial coverage of the major bays that make up Boston Harbor (Figure 2-1). The nine stations designated as “traditional” (T) are those that are sampled for benthic infauna, followed by a full taxonomic analysis of the organisms in each sample. These stations were selected after consideration of previous sampling programs in the harbor (*e.g.*, those conducted for the 301(h) waiver application) and water circulation patterns and other inputs to the harbor (*e.g*., combined sewer overflow). The 52 stations designated as “reconnaissance” (R) are those at which only sediment profile images (SPI) are taken.

2.1.1 Sediment Profile Images

The Boston Harbor SPI survey was conducted in August 2007 at the nine traditional and 52 reconnaissance stations (Figure 2-1). The SPI data supplement the infaunal data to provide a large-scale picture of benthic conditions in the harbor. Sediment profile imagery permits a faster evaluation of the benthos than can be made by traditional infaunal analyses. This qualitative evaluation can then be integrated with the quantitative results from the infaunal and sediment chemistry analyses. The target locations for Boston Harbor SPI stations are listed in Table 2-1. Field data and specific locations of all sediment profile images collected in 2007 are listed in Appendix A1 (Tables A1-1 and A1-2).

2.1.2 Sediment Samples

Samples for analysis of benthic infauna and sedimentary parameters were collected from nine traditional stations in August 2007 (Figure 2-1). Target locations for these stations are given in Table 2-1. Field data and actual station coordinates for each biology and chemistry grab sample, along with a brief description of each sample, are given in Appendix A2 (Tables A2-1 and A2-2).

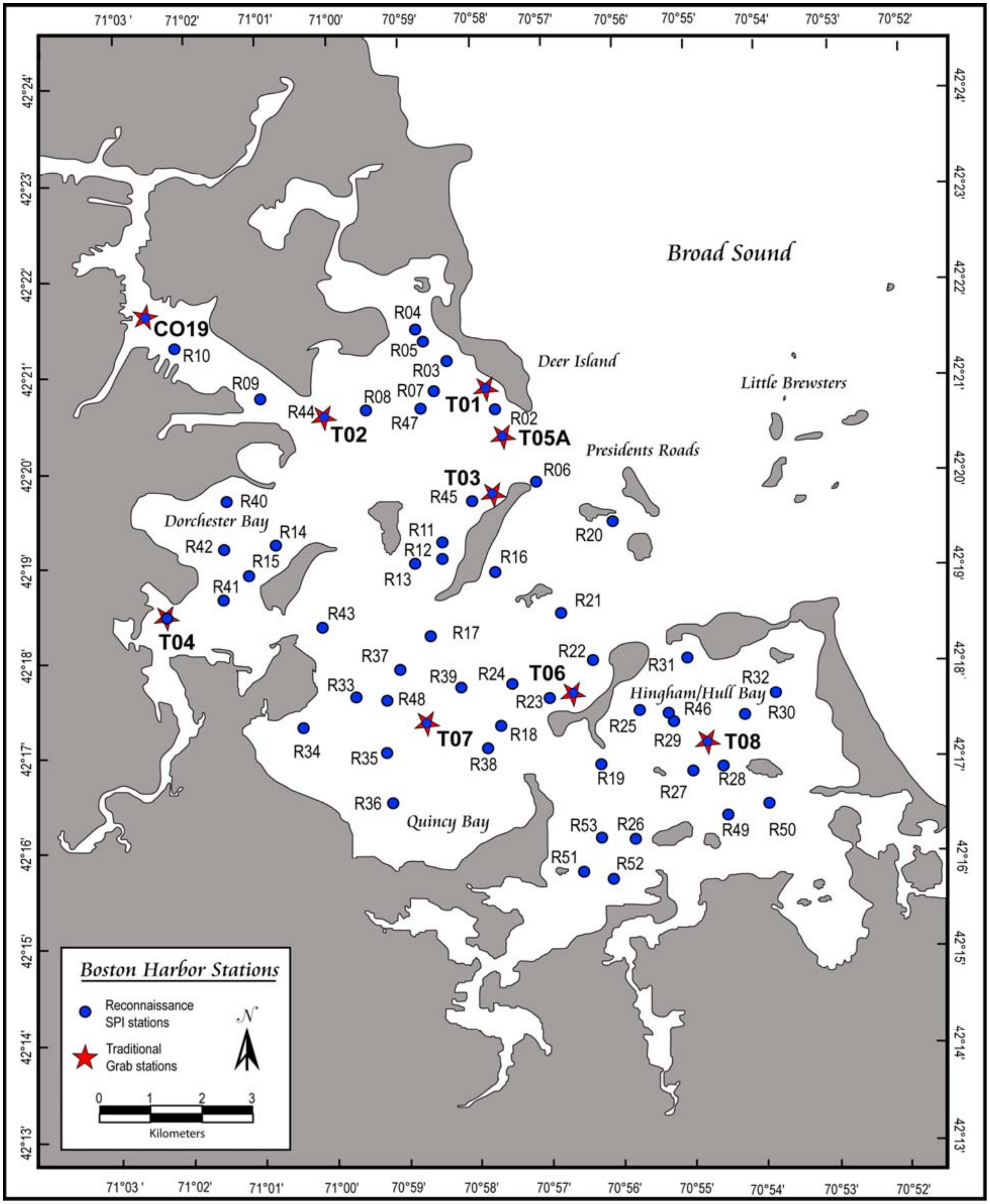

Figure 2-1. Locations of Boston Harbor grab and SPI stations sampled in 2007. Circles indicate Reconnaissance SPI stations sampled in August. Stars show Traditional stations sampled by grab and SPI in August.

Table 2-1. Target locations for Boston Harbor survey grab and SPI stations.

Station	Latitude	Longitude	Depth (m)
Traditional Stations			
C019	42°21.55'N	71°02.71'W	9.3
T01	42°20.95'N	70°57.81'W	4.9
T02	42°20.57'N	71°00.12'W	6.8
T03	42°19.81'N	70°57.72'W	8.7
T04	42°18.60'N	71°02.49'W	4.0
T05A	42°20.38'N	70°57.64'W	17.5
T06	42°17.61'N	70°56.66'W	6.6
T07	42°17.36'N	70°58.71'W	5.9
T08	42°17.12'N	70°54.75'W	11.3
Reconnaissance Stations			
R02	42°20.66'N	70°57.69'W	13.8
R03	42°21.18'N	70°58.37'W	4.5
R04	42°21.52'N	70°58.78'W	7.2
R05	42°21.38'N	70°58.68'W	5.7
R06	42°19.91'N	70°57.12'W	6.7
R07	42°20.85'N	70°58.53'W	5.6
R08	42°20.66'N	70°59.50'W	3.5
R09	42°20.80'N	71°00.98'W	11.6
R10	42°21.32'N	71°02.20'W	12.8
R11	42°19.28'N	70°58.48'W	7.3
R12	42°19.10'N	70°58.47'W	6.1
R13	42°19.03'N	70°58.84'W	6.7
R14	42°19.25'N	71°00.77'W	7.0
R15	42°18.92'N	71°01.15'W	4.4
R16	42°18.95'N	70°57.68'W	8.0
R17	42°18.29'N	70°58.63'W	8.1
R18	42°17.33'N	70°57.67'W	8.0
R19	42°16.92'N	70°56.27'W	9.2
R20	42°19.49'N	70°56.10'W	11.2
R21	42°18.53'N	70°56.78'W	8.7
R22	42°18.02'N	70°56.37'W	9.4
R23	42°17.63'N	70°57.00'W	10.8

Table 2.1 (continued)

Station	Latitude	Longitude	Depth (m)
R24	42°17.78'N	70°57.51'W	7.4
R25	42°17.48'N	70°55.72'W	7.3
R26	42°16.13'N	70°55.80'W	7.0
R27	42°16.83'N	70°54.98'W	4.8
R28	42°16.90'N	70°54.52'W	8.4
R29	42°17.38'N	70°55.25'W	11.0
R30	42°17.43'N	70°54.25'W	3.8
R31	42°18.05'N	70°55.03'W	10.0
R32	42°17.68'N	70°53.82'W	5.0
R33	42°17.65'N	70°59.67'W	5.0
R34	42°17.33'N	71°00.42'W	4.0
R35	42°17.05'N	70°59.28'W	4.8
R36	42°16.53'N	70°59.20'W	5.0
R37	42°17.93'N	70°59.08'W	6.0
R38	42°17.08'N	70°57.83'W	7.0
R39	42°17.73'N	70°58.22'W	8.0
R40	42°19.73'N	71°01.45'W	4.3
R41	42°18.67'N	71°01.50'W	5.5
R42	42°19.18'N	71°01.50'W	3.9
R43	42°18.40'N	71°00.13'W	4.5
R44	42°20.62'N	71°00.13'W	9.3
R45	42°19.70'N	70°58.05'W	6.8
R46	42°17.46'N	70°55.33'W	10.5
R47	42°20.67'N	70°58.72'W	6.5
R48	42°17.61'N	70°59.27'W	5.9
R49	42°16.39'N	70°54.49'W	6.1
R50	42°16.50'N	70°53.92'W	6.1
R51	42°15.80'N	70°56.53'W	3.8
R52	42°15.71'N	70°56.09'W	3.6
R53	42°16.15'N	70°56.27'W	6.0

2.2 Field Program Results

2.2.1 Survey Dates and Samples Collected

A summary of the samples collected during the 2007 Boston Harbor surveys is given in Table 2-2.

Table 2-2. Survey dates and numbers of samples collected in Boston Harbor in 2006.

Survey Type	Survey ID	2006 Date(s)	Samples Collected				
			Inf	TOC	GS	Cp	SPI
SPI	HR071	27–29 Aug					183
Benthic	HT071	1 August	27	27	27	27	

Key: Inf: Infauna, TOC: total organic carbon, GS: grain size, Cp: *Clostridium perfringens*, SPI: individual sediment profile images

2.2.2 Vessel and Navigation

The 2007 Boston Harbor benthic surveys were conducted from Battelle's research vessel, the R/V *Aquamonitor*. Vessel positioning was accomplished with the Battelle Oceans Sampling Systems (BOSS) Navigation system. BOSS consists of a Northstar differential global positioning system (DGPS) interfaced to an on-board computer. The GPS receiver has six dedicated channels and is capable of locking onto six satellites at once. Data were recorded and reduced using NAVSAM© data acquisition software. The system was calibrated at the dock using coordinates obtained from NOAA navigation charts at the beginning and end of each survey day.

At each sampling station, the vessel was positioned as close to target coordinates as possible. The NAVSAM© navigation and sampling software collected and stored navigation data, time, and station depth every 2 seconds throughout the sampling event, and assigned a unique designation to each sample when the sampling instrument hit the bottom. The display on the BOSS computer screen was set to show a radius of 30 m around the target station coordinates (six 5-m rings) for all MWRA benthic surveys. A station radius of up to 30 m is considered acceptable for benthic sampling in Boston Harbor.

2.2.3 Sediment Profile Imagery (SPI)

Dr. Robert Diaz was the Senior Scientist for the 2007 Boston Harbor SPI survey (HR071). Three replicate SPI images were successfully collected at 52 reconnaissance and nine traditional stations. The digital camera captured a 14.1-megabyte RBG image that was recorded to a 1-gigabyte microdrive. The camera was also equipped with a video-feed that sent images to the surface via cable so that prism penetration could be monitored in real-time. In addition, the camera frame supported a video-plan camera mounted to view the surface of the seabed. These images were also relayed to the surface via the video cable and permitted the camera operator to see the seafloor and know exactly when the camera had reached the bottom. The camera operator then switched to the digital still camera and while viewing the camera penetration, chose exactly when to record sediment profile images. Images were usually taken at about 1 and 15 sec after bottom contact.

This sampling protocol helped ensure that at least one usable photograph was produced during each lowering of the camera. The video signal from the video camera showing the surface of the seafloor was recorded on mini-DVD digital videotape for later review. Because the images were viewed by video in real time, it was only occasionally necessary to lower the camera to the seafloor more than three times at each station. The date, time, station, water depth, photo number, and estimated camera penetration were recorded in the field log, with each touchdown of the camera also marked as an event on the NAVSAM©.

The microdrive is capable of recording more images than can be collected during a day of sampling. Consequently, the camera housing does not have to be taken apart as long as the batteries supplying the camera or the strobe do not fail. Camera system upgrades made subsequent to the 2004 SPI survey use the video cable to send some recharging capability to the batteries and permit longer deployments. Consequently, during this survey, the microdrive was replaced and new batteries installed only at the end of each survey day. Images were downloaded from the microdrive to the laptop computer at that time. Digital capability allowed a review of the collected images within 20 min of downloading the microdrive so that it was possible to determine quickly whether or not three analyzable images had been collected at each station. Test shots on deck were not necessary, as loss of battery power to the strobe or camera would have been noticed immediately when the video cable failed to relay any images. While still in the field, images were transferred from the microdrive to a computer and then to a compact disc (CD) for long-term storage.

2.2.4 Grab Sampling

At each station, a 0.04-m^2 Young-modified Van Veen grab sampler was used to collect three replicate sediment samples for infaunal analysis as well as three replicate samples for analysis of sedimentary parameters (*Clostridium perfringens*, sediment grain-size, and TOC). No sediment samples for organics or metals were collected in 2007.

Infaunal samples were sieved onboard with filtered seawater over a 300-μm-mesh sieve and fixed in 10% buffered formalin. For sediment parameter samples, the top 2 cm of the sediment in the grab was removed with a Kynar-coated scoop and homogenized in a clean glass bowl before being distributed to appropriate storage containers. The TOC samples were frozen, whereas the *C. perfringens* and grain size samples were stored on ice in coolers.

3. 2007 SEDIMENT PROFILE IMAGING

by Robert J. Diaz

3.1 Introduction

In the 1980s, nutrient loadings to Boston Harbor were among the highest in the world (Kelly 1997). Over the last 20 years, upgrades in sewage treatment, cessation of discharges into the harbor, and consolidation and relocation of outfalls into a single offshore outfall, which started operation in 2000, have led to major changes in organic loading and primary production within the harbor (Signell et al. 2000, Taylor 2006, Oviatt *et al.* 2007). Bothner *et al.* (1998) and Gallagher and Keay (1998) presented a history of environmental degradation within Boston Harbor. By the 1990s sediment quality started to improve after reductions in pollutant inputs (Eganhouse and Sherblom 2001, Zago *et al.* 2001). Along with these changes in organic loading, contaminant loading, and primary production, the quality of benthic habitats for infauna improved as did the overall infaunal community structure (Maciolek *et al.* 2008, Diaz *et al.* 2008).

This chapter summarizes the continued recovery of benthic habitats within the Harbor using sediment profile images (SPI) to characterize the benthic environment from both physical and biological perspectives (Solan *et al.* 2004) and relates trends to major changes in wastewater disposal within Boston Harbor to long-term changes in habitat condition and quality that could be related to reductions in sewage discharge to the harbor.

3.2 Methods

3.2.1 Image Collection and Analysis

Most of the stations were located in depositional areas of the harbor (Figure 2-1). At each station, a digital sediment profile camera was deployed a minimum of three times (see Chapter 2, this report). Approximately 35 to 75 kg of lead was added to the camera frame to improve penetration at all stations. Analysis of the SPI followed the methods described in Williams *et al.* (2006). Parameters evaluated from SPI are listed in Table 3-1. For quantitative variables, such as aRPD (apparent color redox potential discontinuity) layer depth, data from the three replicates were averaged. For categorical variables, the median or modal value was assigned to a station.

3.2.2 Data Reduction and Statistics

Analysis of variance (ANOVA) was used to test for differences between and within areas for quantitative parameters. Normality was checked with the Shapiro-Wilk test and homogeneity of variance with Bartlett’s test. If variance was not homogeneous, Welch analysis of variance, which allows standard deviations to be unequal, was used in testing for mean differences (Zar 1999). Tukey’s LSD test was used for multiple mean comparisons. Statistical tests were conducted using only stations that were consistently sampled from 1993 with SAS® (SAS Institute, Inc., Cary, North Carolina).

Table 3-1. Parameters measured from Sediment Profile Images.

Parameter	Units	Method	Description
Sediment Grain Size	Modal phi interval	V	An estimate of sediment types present. Determined from comparison of image to images of known grain size
Prism Penetration	cm	CA	A geotechnical estimate of sediment compaction. Average of maximum and minimum distance from sediment surface to bottom of prism window
Sediment Surface Relief	cm	CA	An estimate of small-scale bed roughness. Maximum depth of penetration minus minimum
Apparent Reduction-oxidation Potential Discontinuity Depth (from color change in sediment)	cm	CA	Estimate of depth to which sediments appear to be oxidized. Area of aerobic sediment divided by width of digitized image
Thickness of Sediment Layers	cm	CA	Measure thickness above original sediment surface
Methane/Nitrogen Gas Voids	Number	V	Count
Epifaunal Occurrence	Number	V	Count, identify
Tube Density	Number /cm^2	V	Count
Tube Type			
Burrow Structures	—	V	Identify
Pelletal Layer	cm	V	Measure thickness, area
Bacterial Mats	—	V	Determine presence and color
Infaunal Occurrence	Number	V	Count, identify
Feeding Voids	Number	V	Count, measure thickness, area
Apparent Successional Stage	—	V,CA	Estimated based on all of the above parameters
Organism Sediment Index	—	CA	Derived from RPD, successional stage, gas voids (Rhoads and Germano 1986)

V: Visual measurement or estimate

CA: Computer analysis

3.3 Results

3.3.1 Regional Harbor Trend

From 1993 to 2007 the predominant sediment type appeared to be mixed fine-sand and silt-clay (modal Phi 4.5 to 5.5), which was found at 43% of 881 station-year combinations (Table 3-2). Grain-size for 2007 was similar to recent years with little difference from 2006. In 2007, the only station to change was R22, which became sandier (Table 3-2). Sediments appeared to be finer silt-clay (modal Phi >6) 42% of the time, and sandy, mostly fine to medium sands with a few coarser stations (modal Phi <3), for 15% of the station-year combinations. Grain-size analysis of the grab samples (See Appendix B) and estimated grain-size from SPI were highly correlated (1993 to 2006, $r = 0.83$, $N = 118$, $p = <0.0001$) indicating that the visual estimates are reasonable proxies for sediment grain-size.

From 1993 to 2007, the grain size observed in SPI at 21 stations was consistently muddy (fine-sand-silt-clay to silt-clay). At 38 stations sediments were mostly muddy but appeared to be sandy in at least one year. Four stations were primarily sandy in almost all years: R23 in Nantasket Roads was sandy all years, T08 in Hingham Bay was muddy only in 1999, R06 off Long Island and R19 were sandy in all years, except 2005 and 2006 for R06 and 1996 and 1999 for R19 (Table 3-2). Spatially, there was the same proportion of sandy and muddy stations in the inner and outer sections of the harbor. Regionally, stations in Nantasket Roads, Hingham Bay, Deer Island Flats, and off Long Island were sandier than stations in Dorchester Bay, Quincy Bay, or Charles River. At physically dominated stations with coarse sandy sediments, surface relief was due to sediment grain size (gravel, pebble, or cobble) and bedforms. At biologically dominated stations, surface relief typically consisted of biogenic structures produced by benthic organisms, mostly feeding pits and mounds (Table 3-3 and Appendix C).

The thickness of what appeared to be geochemically oxidized sediments (aRPD) was variable through time but trended up in 2007 relative to 2006 for all Harbor regions (Figure 3-1). Over the years the aRPD oscillated widely but when the effect of region within the harbor and presence of *Ampelisca* spp. tube mats were accounted for there was a significant relationship with time likely related to the reductions in carbon loading to the harbor and to reductions in sedimentary carbon (Diaz *et al.* 2008). Most of the deepening in the aRPD occurred in the outer areas of the harbor (Deer Island Flats, Off Long Island, and Nantasket Roads) prior to diversion of the outfall. Inner areas of the harbor (Charles River, Dorchester Bay, and Quincy Bay) and Hingham Bay did not experience a deepening of the aRPD layer (Figures 3-1 and 3-2).

Over the years of SPI monitoring, biogenic activity associated with the presence of *Ampelisca* spp. had the most influence in deepening the aRPD (Figures 3-2 and 3-3). At some time between 1990 and 1992 there appeared to be an increase in the occurrence of *Ampelisca* spp. tube mats (Figure 3-3). About 20% of images from 1990 had mat densities of *Ampelisca* spp. In 1992, mats increased to about 40% of stations and continued to increase with peaks at 60–65% from 1994 to 1997. Mat densities of *Ampelisca* spp. declined starting in 1998 to 45% and were 13% by 2004 with no tube mats observed with SPI in 2005. *Ampelisca* spp. tube mats reappeared at stations R21 and R30 in 2006, and R02, R20, and R21 in 2007. The total number of stations with *Ampelisca* spp. tubes at any density, from a few tubes to mat densities, also followed a similar pattern (Figure 3-3).

Table 3-2. Modal grain-size estimated from SPI from 1993 to 2007. Sandy sediments were categorized as fine-sand (FS) and medium or coarser (SA), and muddy sediments as mixed fine-sand-silt-clay (MX) or finer silt-clay (SC).

Sta.	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
C019												SC	SC	SC	SC
R02	SC	SC	MX	MX	MX	SC	SC	SC	SC	SC	SC	MX	MX	SC	SC
R03	FS	MX	SA	MX	MX	SC	MX	MX	MX	MX	MX	MX	MX	MX	MX
R04	FS	MX	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC
R05	FS	MX	SC	SC	MX	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC
R06	FS	SA	SA	SA	SA	SA	SA	SA	SA	SA	SA	SA	MX	MX	MX
R07	FS	MX	SC	MX	MX	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC
R08	SA	FS	SA	MX	SA	FS	MX	MX	MX	FS	FS	FS	FS	FS	FS
R09	FS	SC	SC	MX	MX	SC	MX	MX	MX	MX	MX	MX	MX	MX	MX
R10	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC
R11	MX	SC	MX	SC	SC	SC	SC	SC	SC	MX	MX	SC	SC	SC	SC
R12	MX	SC	MX	SC	MX	SC	SC	SC	SC	MX	SC	SC	SC	SC	SC
R13	MX	MX	MX	MX	MX	SA	SC	SC	SC	MX	MX	MX	SA	SC	SC
R14	FS	MX	MX	MX	MX	MX	MX	MX	MX	MX	MX	MX	MX	MX	MX
R15	MX	SC	MX	MX	MX	SC	MX	SC	MX	MX	MX	MX	MX	MX	MX
R16	MX	SC	MX	MX	FS	SC	SC	MX	MX	MX	MX	MX	MX	MX	MX
R17	MX	SC	MX	MX	SC	SC	SC	SC	MX	SC	SC	SC	SC	SC	SC
R18	MX	MX	MX	MX	SC	SC	SC	SC	SC	MX	MX	SC	SC	SC	SC
R19	SA	SA	SA	MX	SA	SA	MX	SA	SA	SA	SA	SA	SA	SA	SA
R20	MX	MX	MX	MX	MX	SA	SC	SC	SC	MX	MX	SC	MX	MX	MX
R21	FS	MX	MX	MX	MX	MX	MX	MX	MX	MX	MX	SC	SC	MX	MX
R22	FS	FS	SA	SA	MX	MX	MX	MX	MX	MX	SA	SA	MX	MX	SA
R23	FS	FS	SA	SA	SA	FS	SA	SA	SA	SA	SA	SA	SA	SA	SA
R24	FS	FS	MX	MX	MX	SC	SC	SC	SC	MX	MX	SC	SC	SC	SC
R25	MX	MX	SC	SC	MX	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC
R26	FS	MX	SC	MX	SA	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC
R27	FS	MX	MX	SC	MX	SC	SC	SC	SC	MX	MX	SC	SC	SC	SC
R28	FS	MX	MX	SC	MX	MX	MX	SC	SC	MX	MX	SC	MX	MX	MX
R29	FS	MX	MX	SC	MX	MX	SC	SC	SC	MX	MX	SC	SC	SC	SC
R30	FS	MX	MX	SC	MX	MX	MX	MX	MX	MX	MX	SC	SC	SC	SC
R31	FS	MX	MX	SC	MX	SC	SC	SC	SC	MX	MX	SC	SC	SC	SC
R32	FS	MX	SC	SC	MX	SC	SC	SC	SC	MX	SC	SC	SC	SC	SC
R33	FS	MX	MX	SC	MX	SC	SC	SC	SC	MX	SC	SC	SC	SC	SC
R34	FS	MX	MX	SC	MX	SC	SC	SC		MX	SC	SC	SC	SC	SC
R35	FS	MX	SC	SC	MX	SC	SC	SC		MX	SC	SC	SC	SC	SC
R36	SA	SA	SA	SA	SA	MX	MX	MX	SA	MX	MX	FS	FS	FS	FS
R37	FS	MX	MX	MX	MX	MX	SC	MX	MX	MX	MX	SC	SC	SC	SC
R38	MX	MX	SC	SC	SC	SC	SC	SC	SC	MX	SC	SC	SC	SC	SC
R39	MX	MX	SA	MX	MX	SC	SC	SC	SC	MX	SC	SC	SC	SC	SC
R40	FS	FS	SC	MX	MX	MX	MX	MX	MX	MX	MX	MX	SC	MX	MX
R41	FS	MX	MX	MX	MX	MX	SC	MX	MX	MX	MX	MX	SC	MX	MX
R42	FS	FS	MX	SA	MX	FS	MX	MX	MX	MX	MX	MX	MX	MX	MX
R43	FS	SC	MX	MX	MX	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC
R44			MX	SC	MX	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC
R45			MX	MX	MX	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC
R46			MX	MX	MX	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC
R47			SC	MX	MX	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC
R48			MX	MX	MX	MX	SC	MX	MX	MX	MX	MX	MX	MX	MX
R49			MX	SC	MX	MX	SC	MX	MX	MX	MX	MX	SC	SC	SC
R50			MX	MX	MX	MX	MX	MX	MX	MX	MX	MX	MX	MX	MX
R51			MX	SC	MX	MX	MX	MX	MX	MX	MX	MX	MX	MX	MX
R52			MX	SC	MX	MX	MX	MX	MX	MX	MX	MX	MX	MX	MX
R53			MX	MX	SA	MX	MX	MX	MX	FS	FS	MX	MX	MX	MX
T01	FS	SA	MX	SA	MX	MX	MX	MX	MX	MX	MX	MX	MX	MX	MX
T02	MX	MX	SC	SA	MX	SC	SC	MX	MX	SC	SC	SC	SC	SC	SC
T03	MX	SC	SC	MX	MX	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC
T05A		SC	SC	SC	MX	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC
T04	SC	FS	MX	SA	SA	FS	MX	SA	SA	SA	MX	MX	MX	MX	MX
T06	FS	MX	SC	SC	MX	MX	MX	SC	SC	MX	MX	MX	MX	MX	MX
T07	MX	MX	SC	MX	MX	SC	SC	MX	MX	MX	MX	MX	MX	SC	SC
T08	SA	SA	SA	SA	SA	FS	MX	SA	SA	SA	SA	SA	SA	SA	SA

Table 3-3. Summary of SPI parameters for 2007 harbor stations.

Sta	PEN Ave	RPD Ave	Grain Size		Surface Rough.	Amphi. Tubes	Worm			Oxic Voids	Anaerobic Voids	Gas Voids	Modal	
			Modal	Max			Tubes	Infauna	Burrow				SS	OSI
C019	15.9	1.7	SICL	SI	PHY	NONE	NONE	0.0	0.0	0.0	2.7	0.0	I	3.7
R02	16.3	7.3	SICL	SI	BIO/PHY	MAT	FEW	2.3	1.3	6.7	1.0	0.0	II-III	10.0
R03	14.5	5.1	SIFS	FS	PHY	SOME	FEW	2.0	1.7	3.7	0.3	0.0	III	11.0
R04	16.9	2.0	SICL	SI	PHY	NONE	NONE	0.0	0.7	2.3	1.3	0.0	I-III	6.7
R05	15.8	2.4	SICL	SI	PHY	NONE	NONE	0.0	1.0	2.7	1.0	0.0	I-III	8.7
R06	1.7	0.7	FSSI	PB	PHY	NONE	MANY	0.0	0.0	0.0	0.0	0.0	I	2.0
R07	13.7	7.9	SICL	SI	BIO/PHY	FEW	FEW	7.3	1.3	5.0	0.0	0.0	III	11.0
R08	3.2	>3.2	FS	PB	PHY	NONE	SOME	0.7	0.0	0.0	0.0	0.0	I	IND
R09	13.0	2.1	SIFS	FS	PHY	NONE	NONE	0.0	0.7	1.3	0.0	0.0	III	8.3
R10	16.0	3.4	SICL	SI	PHY	NONE	NONE	0.3	0.0	1.3	0.7	1.3	III	7.3
R11	15.1	3.3	SICL	SI	BIO/PHY	SOME	FEW	0.0	1.0	1.0	0.0	0.0	II-III	8.7
R12	14.8	2.3	SICL	SI	PHY	NONE	FEW	0.0	0.7	1.7	0.7	0.0	III	8.7
R13	7.9	1.1	SICL	PB	PHY	NONE	SOME	0.0	0.3	0.3	0.0	0.0	I	4.3
R14	11.8	2.2	FSSI	FS	PHY	NONE	NONE	0.3	0.0	2.0	0.3	0.0	III	8.3
R15	11.1	1.3	FSSI	FS	PHY	NONE	MANY	0.7	0.3	1.7	0.0	0.0	I-III	5.7
R16	9.0	1.5	FSSI	PB	PHY	FEW	SOME	1.3	0.3	1.3	0.3	0.0	II-III	6.0
R17	14.1	5.6	SICL	SI	PHY	FEW	FEW	3.0	1.7	5.0	0.0	0.0	II-III	9.3
R18	13.9	1.8	SICL	SI	BIO/PHY	FEW	FEW	1.0	0.3	1.7	0.7	0.0	II-III	7.0
R19	3.2	>3.2	FSMS	PB	PHY	NONE	SOME	0.0	0.0	0.0	0.0	0.0	I	7.0
R20	14.0	2.6	SIFS	FS	BIO	MAT	FEW	3.0	1.0	2.7	0.0	0.0	II-III	8.0
R21	12.2	5.4	FSSI	FS	BIO	MAT	FEW	3.0	2.3	3.3	0.0	0.0	II-III	10.0
R22	5.0	1.9	FSMS	PB	PHY	NONE	SOME	0.0	0.0	0.0	0.0	0.0	I	5.5
R23	4.2	2.3	FSMS	PB	PHY	SOME	NONE	0.0	0.0	0.0	0.0	0.0	I-II	5.5
R24	13.8	3.1	SICL	SI	BIO/PHY	SOME	FEW	3.0	1.0	1.3	0.0	0.0	II-III	8.7
R25	18.1	1.7	SICL	SI	PHY	NONE	SOME	2.7	2.7	1.0	1.0	0.0	I-III	8.0
R26	13.2	2.3	SICL	SI	BIO/PHY	NONE	NONE	1.0	0.0	2.0	0.0	0.0	III	8.3
R27	14.9	4.5	SICL	SI	BIO/PHY	FEW	SOME	3.0	1.7	4.3	0.3	0.0	II-III	9.7
R28	9.0	2.8	FS/FSSI	PB	PHY	SOME	SOME	1.0	1.3	0.7	0.0	0.0	I-II	7.0
R29	12.3	2.0	SICL	SI	BIO/PHY	SOME	SOME	2.0	0.7	1.7	0.0	0.0	II-III	7.0
R30	12.0	1.9	SICL	SI	PHY	SOME	FEW	6.3	2.0	3.7	0.0	0.0	II-III	7.0
R31	13.1	2.6	SICL	SI	PHY	NONE	SOME	3.3	1.0	1.7	0.0	0.0	I-III	8.7
R32	14.9	2.9	SICL	SI	PHY	NONE	SOME	1.0	1.3	3.3	0.0	0.0	III	9.3
R33	15.9	2.0	SICL	SI	PHY	NONE	FEW	0.3	1.0	1.3	0.7	0.0	III	8.0
R34	14.3	2.3	SICL	SI	BIO/PHY	NONE	SOME	1.3	3.0	2.3	0.3	0.0	III	9.0
R35	14.3	1.5	SICL	SI	PHY	NONE	NONE	1.3	0.7	0.3	0.0	0.0	I	5.0
R36	2.9	1.6	FS	PB	PHY	NONE	FEW	0.0	0.0	0.0	0.0	0.0	I	4.0
R37	14.8	2.4	SICL	SI	PHY	NONE	FEW	0.7	0.3	1.3	0.0	0.0	III	7.3
R38	13.6	2.9	SICL	SI	BIO/PHY	SOME	SOME	2.0	2.7	4.7	0.7	0.0	II-III	8.3
R39	14.3	2.2	SICL	SI	PHY	NONE	FEW	2.0	1.0	1.7	0.0	0.0	II-III	6.7
R40	9.5	0.7	SIFS	FS	PHY	NONE	FEW	4.3	1.7	1.3	0.0	0.0	III	5.3
R41	14.2	2.0	SIFS	FS	BIO/PHY	NONE	FEW	0.0	0.0	1.7	0.0	0.0	III	7.0
R42	10.4	1.4	SIFS	FS	BIO/PHY	NONE	NONE	0.7	2.0	2.0	0.0	0.0	III	7.3
R43	14.8	1.2	SICL	SI	BIO/PHY	NONE	FEW	1.0	1.0	2.3	1.3	0.0	III	7.3
R44	14.8	3.5	SICL	SI	BIO/PHY	NONE	NONE	0.7	3.0	2.7	1.0	0.7	III	9.0
R45	13.9	2.7	SICL	SI	BIO/PHY	FEW	FEW	0.7	1.0	2.0	1.3	0.0	II-III	8.3
R46	14.0	2.0	SICL	SI	BIO/PHY	SOME	FEW	1.3	1.0	1.7	0.3	0.0	II-III	7.3
R47	12.9	5.1	SICL	SI	BIO/PHY	FEW	FEW	6.3	2.3	3.0	0.3	0.0	II-III	10.0
R48	12.7	1.0	SIFS	FS	PHY	NONE	NONE	0.3	0.3	1.0	0.3	0.0	III	7.0
R49	13.7	1.8	SICL	SI	PHY	NONE	SOME	1.0	1.3	3.3	0.0	0.0	III	8.0
R50	10.2	2.9	FSSI	FS	PHY	SOME	SOME	0.3	1.7	1.0	0.0	0.0	II-III	8.3
R51	9.4	1.8	FSSI	FS	PHY	FEW	NONE	0.7	0.3	0.7	0.0	0.0	II-III	7.3
R52	9.4	2.0	FSSI	FS	PHY	NONE	NONE	0.7	2.0	2.0	0.0	0.0	III	8.0
R53	8.1	2.0	FS/FSSI	FS	BIO/PHY	NONE	NONE	0.3	3.3	1.3	0.0	0.0	III	8.0
T01	9.9	1.9	FSSI	FS	BIO/PHY	NONE	SOME	0.7	2.3	0.3	0.0	0.0	I	5.3
T02	14.6	3.2	SICL	SI	BIO/PHY	SOME	FEW	1.0	3.3	4.7	0.0	0.0	III	10.0
T03	13.6	2.7	SICL	SI	PHY	SOME	SOME	1.7	0.3	1.3	1.0	0.0	II-III	8.0
T04	16.6	1.8	SICL	SI	PHY	NONE	NONE	0.7	0.3	0.3	0.0	0.0	I	5.3
T05A	9.8	3.5	FS/FSSI	FS	PHY	SOME	SOME	0.3	0.7	1.0	0.7	0.0	II-III	9.0
T06	11.5	1.6	SIFS	FS	BIO/PHY	FEW	FEW	1.7	2.3	3.0	0.0	0.0	II-III	6.7
T07	14.0	1.6	SICL	SI	PHY	NONE	SOME	0.0	0.3	1.0	1.7	0.0	I-III	6.0
T08	2.7	>2.7	FSMS	MS	PHY	SOME	SOME	0.0	1.0	0.0	0.0	0.0	I-II	IND

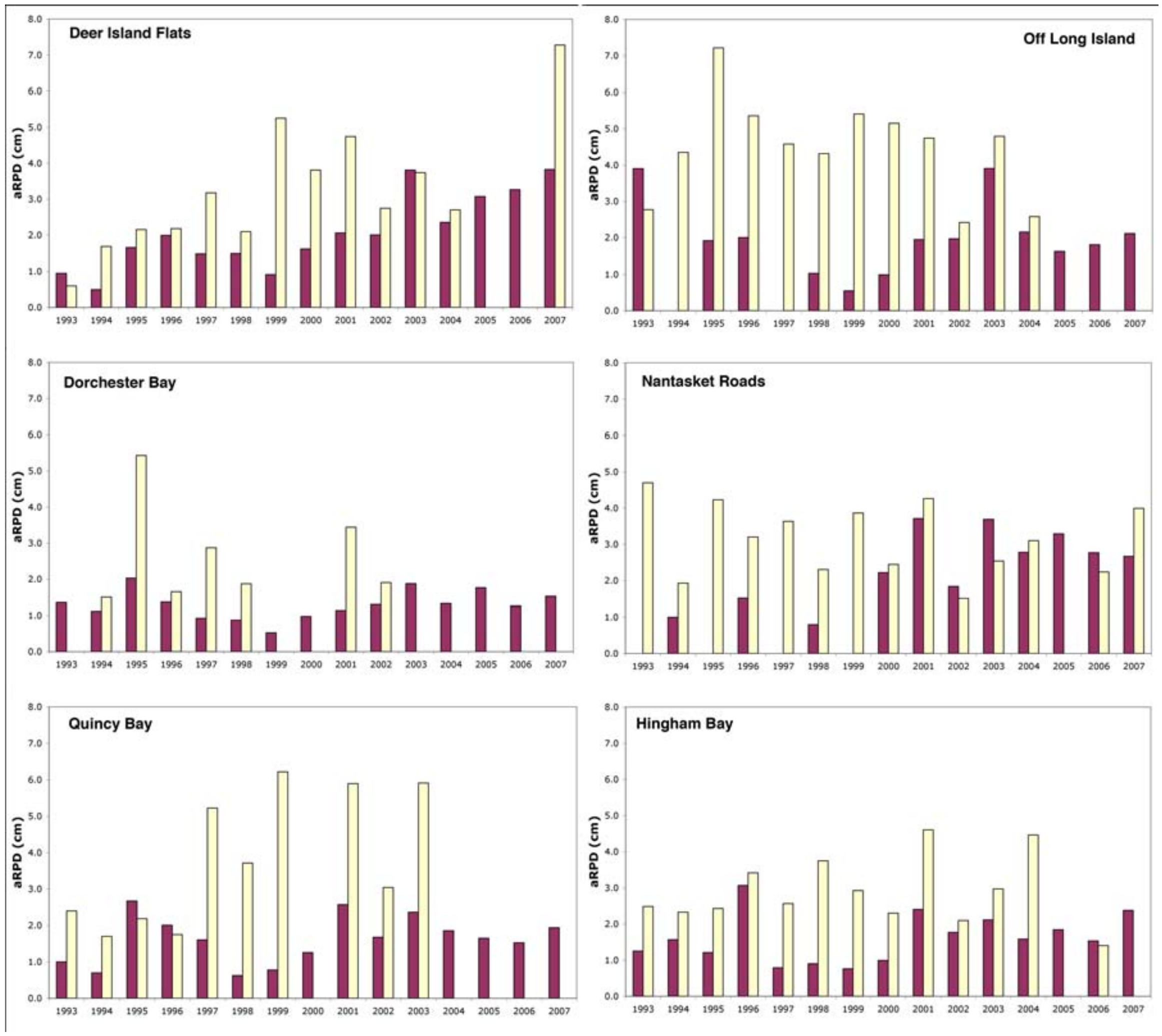

Figure 3-1. Average aRPD layer depth by year and harbor region. Red bars (left) are stations without and yellow bars (right) are stations with *Ampelisca* spp. tube mats.

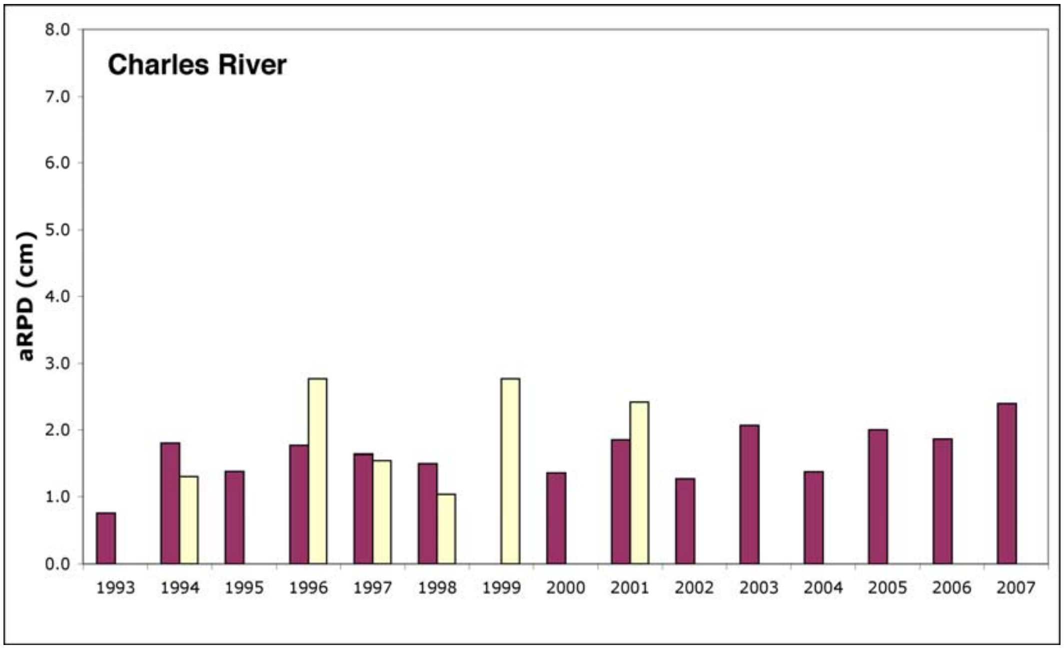

Figure 3-2 Average aRPD layer depth by year for the Charles River. Red bars are stations without and yellow bars are stations with *Ampelisca* spp. tube mats.

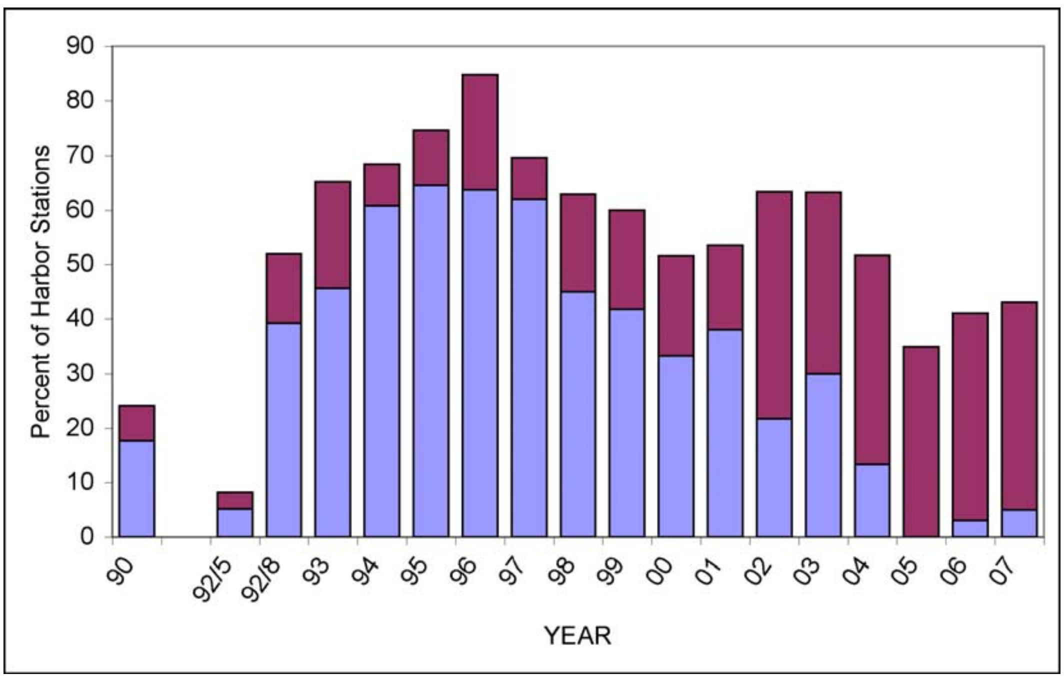

Figure 3-3. Percentage of stations with *Ampelisca* spp. tube mats (light blue) and the total percentage of stations with *Ampelisca* spp. tubes.

The trend for surface sediments to be less biologically dominated continued into 2007. This trend may be related to the shifts in proportion of infaunal feeding types away from sediment-surface-feeding species to burrowing and subsurface feeding species that produce fewer surficial biogenic structures (Blake *et al.* in prep.). The number of infaunal organisms per image in 2007 was significantly higher at stations with biological or biological and physically dominated surfaces (1.9±0.33 infauna/image, mean ±SE) relative to physically dominated surfaces (1.0±0.25 infauna/image) (ANOVA, df = 1, F = 4.8, p = 0.032). Similarly significant patterns of higher mean values at biologically dominated stations were observed for number of burrows and feeding voids per image.

The biogenic sediment reworking observed at many stations was consistent with the presence of a more mature infaunal community. Evidence of equilibrium successional fauna (Stage III)— for example, feeding voids (oxic and anaerobic)—was observed at 73% of year-station combinations for 1993–1994 and 1998–2006 (the presence of voids was not recorded from 1995 to 1997). In 2007, feeding voids occurred at 87% of the stations. Recruitment by small (<1 mm diameter) tube-building species, likely pioneering successional fauna (Stage I), was evident at 31% of stations in 2007. This is a decline from a high of 76% of Stage I presence in previous years (Diaz *et al.*2008).

3.3.2 Trends Linked to Changes in Loadings from Wastewater

Trends in benthic habitat conditions from 1993 to 2006 relative to changes in wastewater discharges and loading to the harbor were assessed by Diaz *et al.* (2008). Much of the change in habitat quality and community structure appeared to be related to population dynamics of *Ampelisca* spp. With the reductions in loadings to the harbor, *Ampelisca* spp. and other benthos relied on inventories of organic matter stored in the sediment for maintaining large populations. By 2001, period IV as defined by Taylor (2006), TOC at T02 (flux station BH02) and T03 (BH03) declined slightly relative to Taylor periods II and III (1992 to 1998 and 1999 to 2000, respectively). For station T03, the decline in TOC for periods III and IV was more pronounced (Tucker *et al.* 2006). The decline in tube mats from periods II to IV would also be consistent with reduction of sediment organic inventories as large amounts of organic matter are needed to sustain mat densities of *Ampelisca* spp. In 2007 this trend for lower TOC likely continued as sediment color (Appendix C) and levels of biogenic activity appeared similar to previous years in period IV (Figure 3-4 and Appendix B).

To determine if the reductions in loadings associated with reduced wastewater discharge and improved treatment affected benthic habitat quality for infauna within the harbor, stations nearest the old Nut Island (within 2 km: R18, R22, R23, R24, and T06; within 4 km: R21, R38, R39, and T07) and Deer Island (within 2 km: R02, R03, R07, R47, T01, and T05A; across channel: R06, R45, and T03) outfalls (Figure 2-1). These stations should show the greatest change relative to relocation of discharges and improved treatment. For Nut Island, Diaz *et al*. (2008) found no significant effect of proximity to outfalls for any of the SPI parameters examined. At Deer Island, there were significant differences in burrows, an indicator of subsurface biogenic activity, with the odds of burrows being present greater further away from the outfalls. Data from 2007 did not change the patterns observed through 2006. The aRPD layer depth, and number of infauna, burrows, and voids, both oxic and anaerobic, observed in SPI all followed similar patterns for the last three years. The exception was an increase in the number of voids per image at stations 2 to 4 km away from the old Nut Island outfall (Figures 3-5 and 3-6).

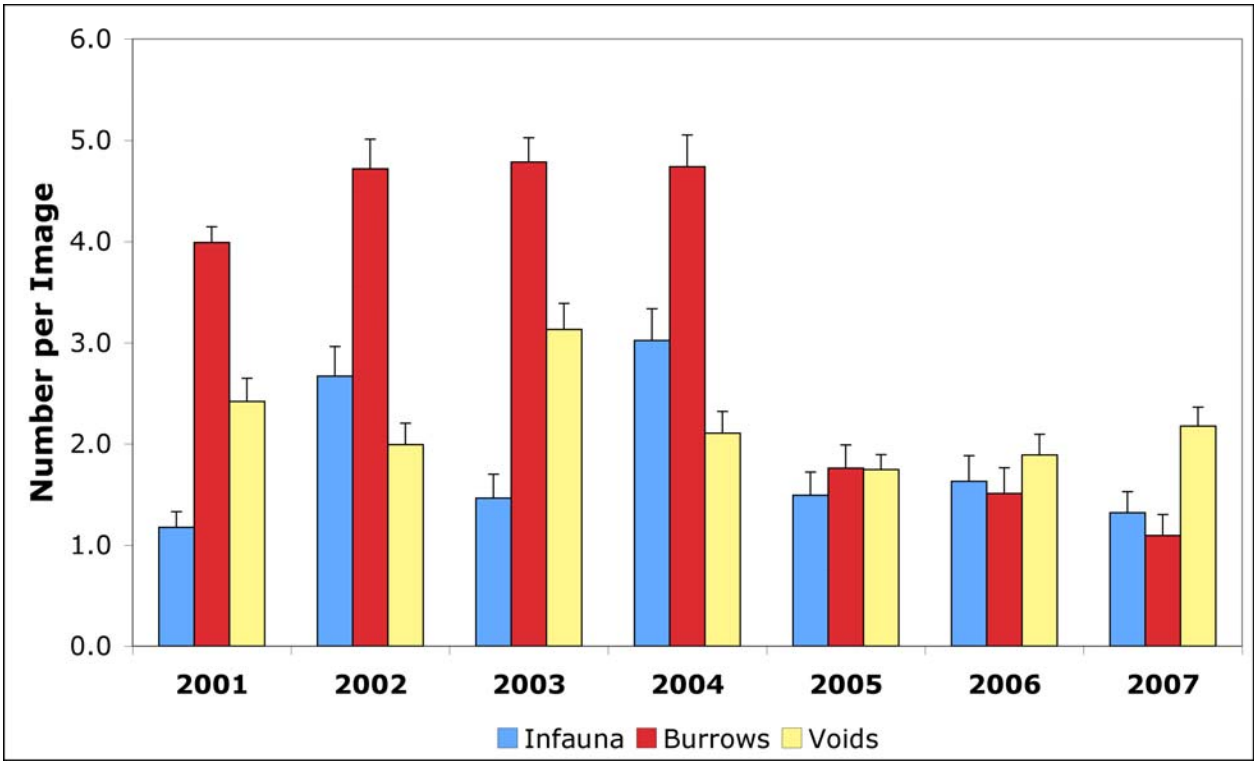

Figure 3-4. **Average biogenic structures (infauna, burrows, and total voids) per SPI image for Taylor (2006) period IV (after diversion of outfall).**

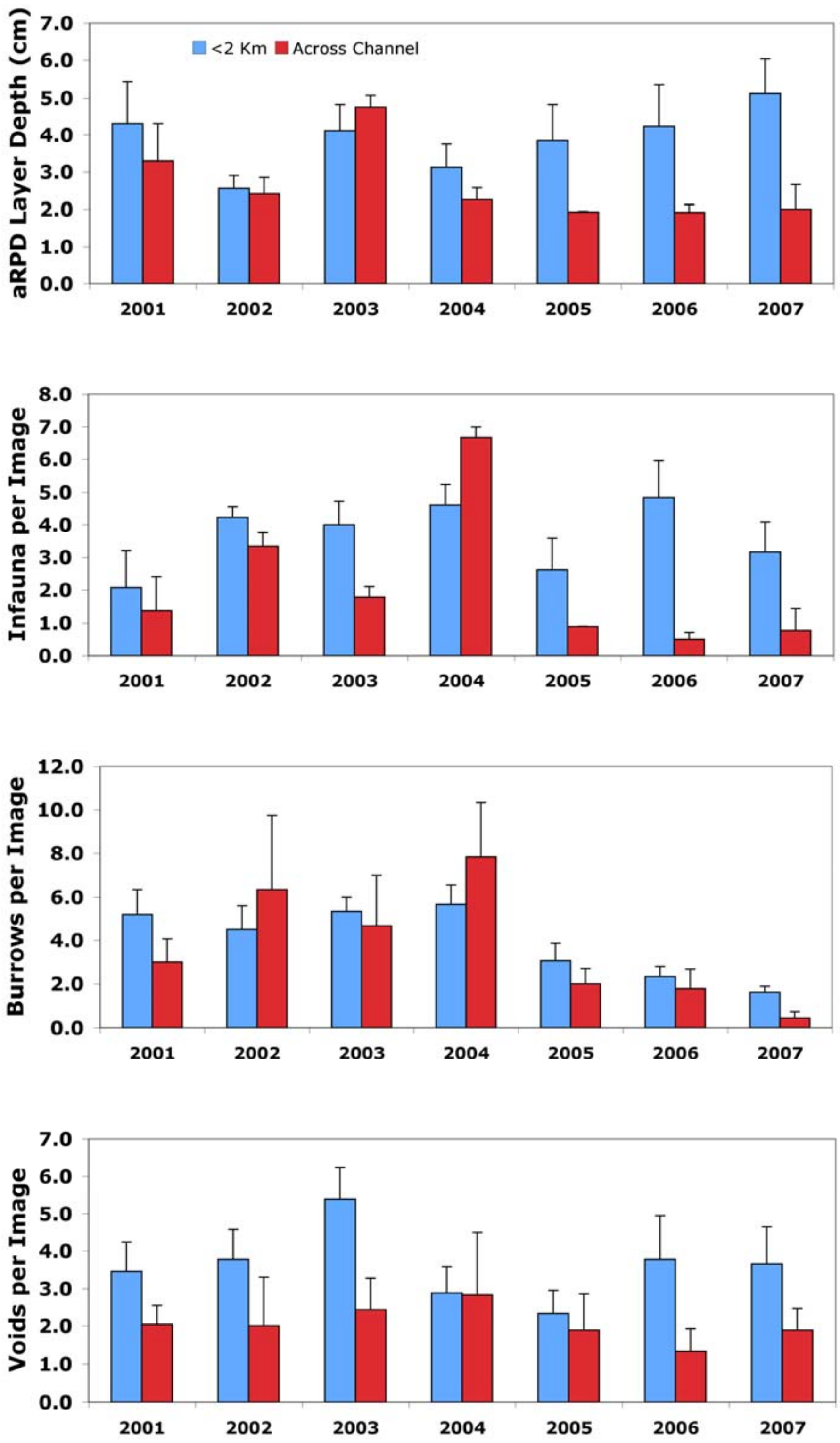

Figure 3-5. Average aRPD and biogenic structures (infauna, burrows, and total voids) per SPI image for stations <2 km (blue bars) and stations across the channel from the outfall (red bars) from the old Deer Island outfall.

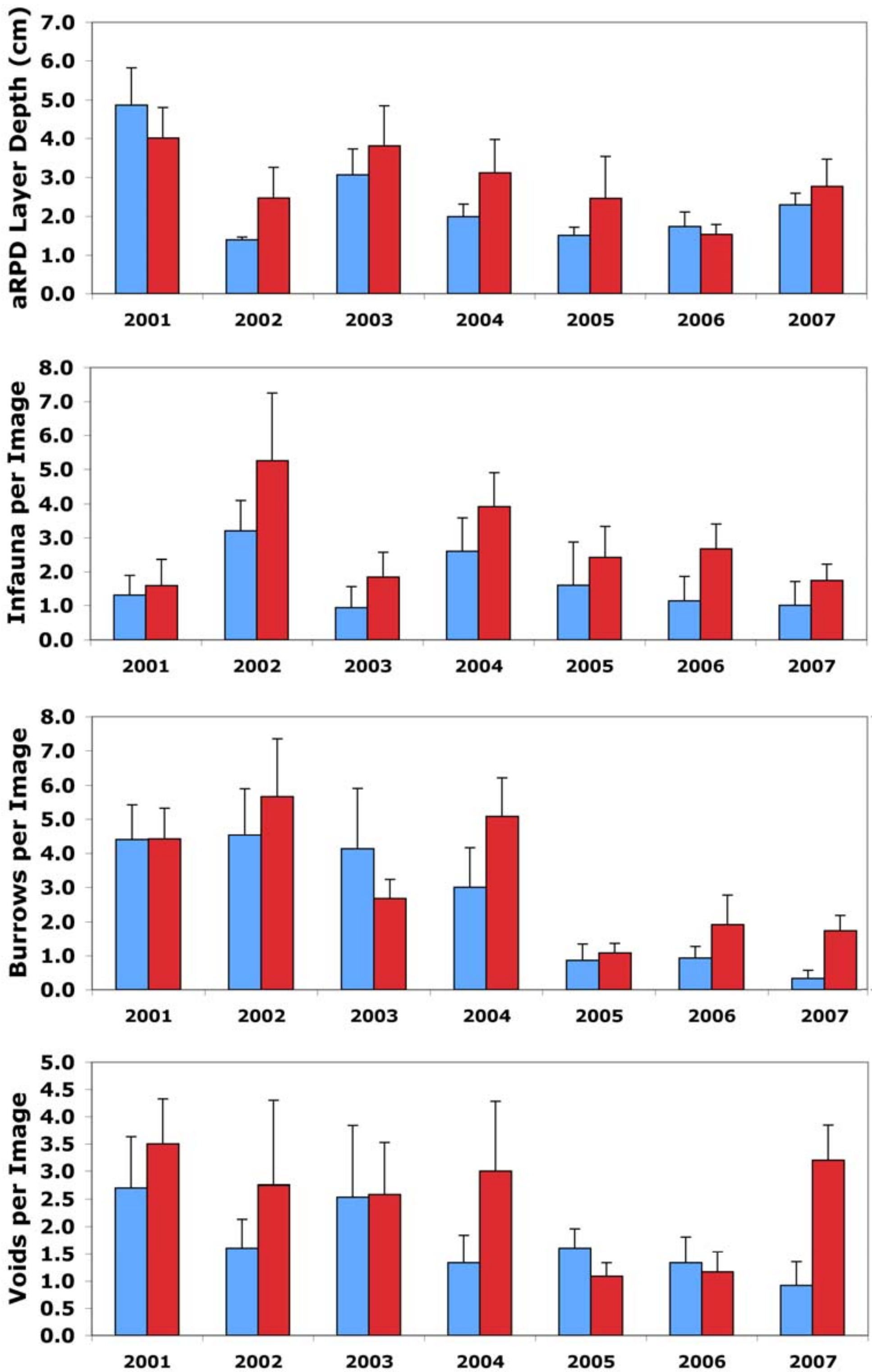

Figure 3-6. Average aRPD and biogenic structures (infauna, burrows, and total voids) per SPI image for stations <2 km (blue bars) and stations 2 to 4 km (red bars) from the old Nut Island outfall.

3.3.3 Benthic Habitat Quality

Benthic habitat quality for infauna at the grab stations from 1992 to 2006 was assessed using sediment and infaunal data from grab samples (total abundance, Fisher's log-series *alpha*, mean Phi, percent gravel, and TOC) and SPI image data (RPD, amphipod tube mats, and estimated successional stage) by Diaz *et al.* (2008). The addition of 2007 data did not change the cline of habitat quality. Principle components analysis (the first three axes accounted for 77% of variance) revealed a cline of relative habitat quality from lowest quality at station T04, progressing to intermediate habitat quality for T01, T02, T03, and T07, and highest habitat quality at T06, T05A, and T08 (Figure 3-7).

Station T04 had the finest sediments with the highest TOC and the lowest values for community structure and SPI variables. Stations T05A and T08 were opposite of T04 with lower TOC and higher community structure and SPI variables. Stations T01 and T07 were separated from the other stations primarily because of low total and *Ampelisca* spp. abundance, and shallower RPD layer depths. Stations T02, T03, and T06 were near the center of the habitat cline in 2007 (Figure 3-7).

Microalgal mats, an additional indicator of good benthic habitat quality for infauna, were present at 18% of the harbor stations in 2007 (CO19, T04, T06, R33, R34, R37, R41, R42, R43, R51, and R52) (Appendix B and Figure 3-8). The presence of microalgal mats at stations deeper than 6 m (CO19, T06, and R37) is an indicator of improved water clarity from a combination of lower total suspended solids and lower planktonic biomass (Taylor 2006, Oviatt et al. 2007). The majority of the shallower (<6 m) stations with microalgal mats were in Dorchester and Quincy Bays and may indicate improving benthic habitat quality in the inner parts of the harbor that up until now have not shown much improvement.

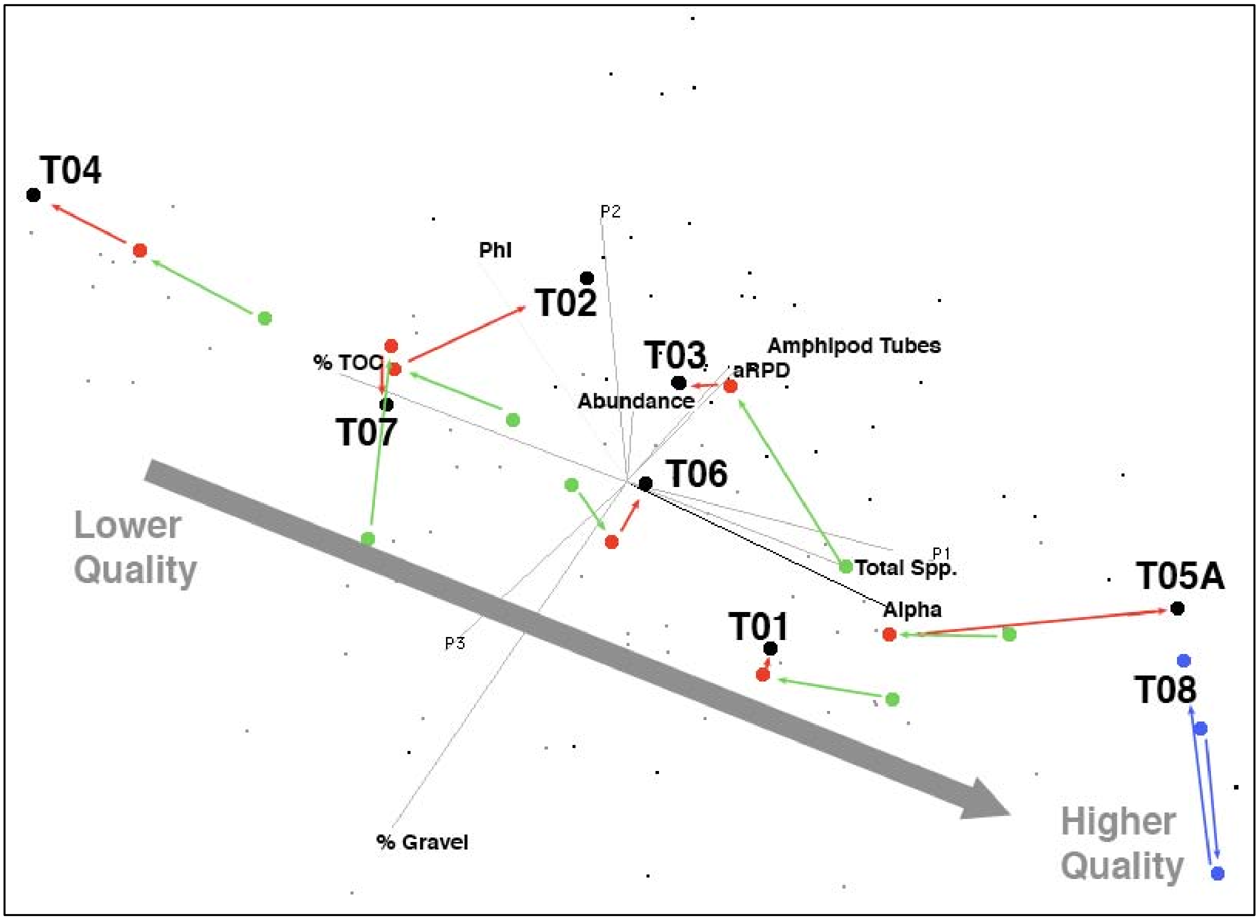

Figure 3-7. Biplot of eight sediment, infauna, and SPI variables from 1993 to 2007 from PCA of station-averaged data. Plot is arranged looking down on the first three principle component axes (P1, P2, and P3) at about a 45° angle. Larger black dots indicate the position of each station within the ordination space for 2007. Red dots are positions in 2006. Green dots are positions in 2005. Blue dots are positions for station T08 from 2002 through 2005; in 2006 and 2007 the aRPD at T08 was deeper than prism penetration. Gray arrow indicates general cline of habitat quality from lower at T04 to higher at T08.

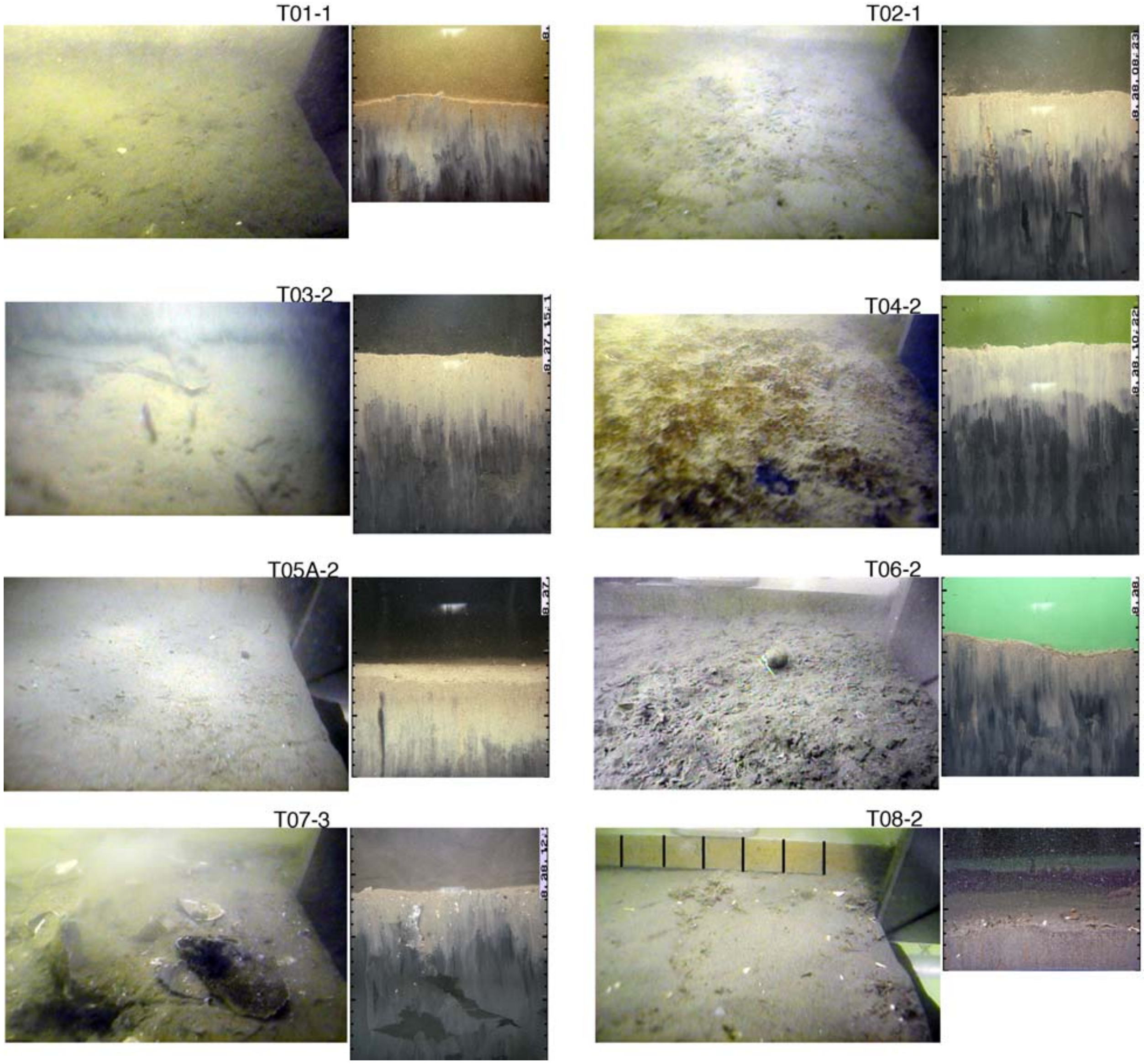

Figure 3-8. Mosaic of surface and SPI images for grab stations in 2007. Scale on side of SPI is in 1-cm intervals. Scale for surface video is in 5-cm intervals (see T08).

3.4 Summary

In 2007, Boston Harbor continued to show signs of improved benthic habitat quality for infauna. Based on the patterns of association between the sediment, infauna, and SPI variables, the cline of relative habitat quality in Boston Harbor, from lower habitat quality at station T04 to higher habitat quality at T08 was still present in 2007 (Figure 3-7). The presence of microalgal mats in the Charles River, near the old Nut Island outfall, and in Dorchester and Quincy Bays may be an indication that areas further away from the Harbor mouth are starting to show signs of improved benthic habitat quality. However, most of the stations in Dorchester and Quincy Bays appear to be characterized by anaerobic processes and carbon accumulation. In contrast, stations near the harbor mouth appeared more aerobic with little carbon accumulation. Overall, the improvements in wastewater treatment and moving the outfall offshore, as well as improvements to the discharges from the Combined Sewer Overflows (CSOs), have led to improvements in benthic habitats within Boston Harbor by favoring processes that enhance bioturbation rates. While portions of the inner harbor have lagged, there are now signs of improvement.

4. 2007 SOFT-BOTTOM INFAUNAL COMMUNITIES

by Nancy J. Maciolek

4.1 Introduction

Nine stations in Boston Harbor were sampled in August 2007 for soft-bottom benthic infauna. Seven of these stations have been sampled consistently since September 1991; the eighth, T05A, replaced T05 in 1993. A ninth station, C019, was added in 2004 to monitor changes that may occur during upgrading of the combined sewer overflow (CSO) system. Station locations are indicated in Figure 2-1 (Chapter 2, this report).

In the early years of sampling in Boston Harbor, stations in the northern part of the harbor, particularly those near Deer Island flats, were characterized as polluted, with low species richness, diversity, and evenness (Blake and Maciolek 1990, Maciolek *et al.* 2004). Stations in the southern harbor, *i.e*., Quincy, Hingham, and Hull Bays, were noticeably different, with a richer, more diverse fauna. Differences could also be seen between stations closer to shore (*e.g*., T01, TO2, T04) versus stations closer to Massachusetts Bay (*e.g.*, T08). As changes in terms of the composition and amount of sewage dumped into the harbor have been implemented, the stations in the nearshore, northern part of the harbor have exhibited more changes in the number of species and diversity of the benthic fauna than have the stations in the southern part. T04 remained relatively unchanged until recently, when discharges from the nearby Fox Point CSO were modified to allow storm water only. MWRA formally decommissioned the Fox Point CSO facility on November 1, 2007.

4.2 Methods

4.2.1 Laboratory Analyses

Samples were preserved with formalin in the field (see Chapter 2), and in the laboratory were rinsed with fresh water over 300-μm-mesh screens and transferred to 70–80% ethanol for sorting and storage. To facilitate the sorting process, all samples were stained in a saturated alcoholic solution of Rose Bengal at least overnight, but no longer than 48 h. After rinsing with clean alcohol, all organisms, including anterior fragments, were removed and sorted to major taxonomic categories such as polychaetes, arthropods, and mollusks. After the samples were sorted, the organisms were identified to the lowest practical taxonomic category, usually species. Voucher specimens of any species newly identified from the harbor samples were kept as part of the MWRA reference collection.

4.2.2 Data Analysis

Preliminary Data Treatment—Prior to performing any analyses, several modifications were made to the database (Appendix C1). These modifications were generally similar to those performed in previous years as given in the standard operating procedure (SOP) for this project (Williams *et al.* 2006, with the exception that the polychaete species *Pholoe minuta*, *P. tecta*, and *P*. spp. were not merged into a single taxon prior to analysis of the 2007 results.

For analyses on the data pooled to one sample per year, the following modifications were made: (1) data from 1991 and 1992 were not used, since T05A was not sampled in those years, (2) C019 was not included, (3) the missing replicates from T03-2000 and T05A-2001 were replaced by averaging the other two replicates in order to have similar numbers of samples in each year, and (4) *Pholoe minuta* and *P. tecta* were merged (but the 33 specimens of *Pholoe* spp. were not included).

Calculations of abundance included all infaunal taxa occurring in each sample, whether identified to species level or not, but did not include epifaunal or colonial organisms. Calculations based on species (number of species, dominance, diversity, evenness, cluster and principle components analysis) included only those taxa identified to species level, or those treated as such (see Appendix C1).

Statistical Analysis—Initial inspection of the benthic data included production of summaries of species densities by sample, tables of species dominance, and lists of numbers of species and numbers of individuals per sample. Data were inspected for any obvious faunal shifts or species changes between stations. Following these preliminary inspections of the data, univariate and multivariate methods were used to assess community patterns and structure.

Univariate Measures —PRIMER v.6 (Clarke and Gorley 2006) was used to calculate several diversity indices, including Shannon's H′ (base 2), Pielou's evenness value J′, and Fisher's log-series *alpha*. Magurran (1988) classifies diversity indices into three categories: (1) species richness indices (*e.g.*, rarefaction); (2) species abundance indices (*e.*g., log-series *alpha*), and (3) indices based on the proportional abundances of species (*e.g*., Shannon index). The Shannon index, which is based on information theory, has been popular with marine ecologists for many years, but this index assumes that individuals are randomly sampled from an infinitely large population and that all species are present in the sample (Pielou 1975, Magurran 1988): neither assumption correctly describes the environmental samples collected in most marine benthic programs. Fisher's log-series model of species abundance (Fisher *et al.* 1943) has been widely used, particularly by entomologists and botanists (Magurran 1988). Taylor's (1978) studies of the properties of this index found that it was the best index for discriminating among subtly different sites, and May (1975) demonstrated that Sanders-Hurlbert rarefaction curves are often identical to those produced under the assumption that the distribution of individuals among species follows a log-series distribution. Gallagher's program *rarefyl* was used to construct rarefaction curves for the pooled data.

Multivariate Measures —**Similarity analysis** was performed using both CNESS (chord-normalized expected species shared) (Trueblood *et al.* 1994) and the Bray-Curtis index (Bray and Curtis 1957). All similarity matrices were clustered using a hierarchical agglomerative clustering technique, with group average sorting.

CNESS is calculated from the expected species shared (ESS) between two random draws of *m* individuals from two samples. For this project, the optimal value of *m* was determined to be 15 for annual data and 20 for multiyear comparisons. CNESS is included in the COMPAH96 package, originally written by Dr. Donald Boesch and now available from Dr. Eugene Gallagher at the University of Massachusetts, Boston (http://www.es.umb.edu/edgwebp.htm).

The Bray-Curtis similarity analyses were based on a square-root transformation of the data (performed in order to diminish the impact of numerically dominant species) and were carried out in PRIMER v.6 (Clarke and Gorley 2006). Previous analyses in recent years have used a fourth-root transformation; this results in lower similarity levels but with the exception of the placement of one or two samples, gives essentially the same pattern as the square-root transformation.

The PRIMER routine ANOSIM (analysis of similarities) was used to test the null hypothesis that there are no differences in harbor communities, either within 2007 or between years. This test is based on the matrix generated by a similarity test, in this case, Bray-Curtis. Clarke and Gorley (2001) discuss the use of this test as a replacement for ANOVA, and interpretation of R values is discussed in Chapman and Underwood (1999).

Another PRIMER routine, SIMPER (similarity percentages), which is based on the Bray-Curtis similarity matrix, was used to examine the species that both typify the major groups and discriminate between them (Clarke and Gorley 2006).

Ordination techniques used to visualize distances among samples include Principal Components Analysis of hypergeometric probabilities (PCA-H) applied to the CNESS results (see Trueblood *et al.* 1994 for details), and multidimensional scaling (MDS) applied to the Bray-Curtis results (Clarke and Gorley 2006).

The PCA-H method is a multistep analysis that produces a metric scaling of the samples in multidimensional space, as well as a Euclidean distance biplot (Gabriel 1971) of the major sources of CNESS variation, *i.e.*, the species that contribute the most to the distances among samples. These species are determined using matrix methods adapted from Greenacre's correspondence analysis (Greenacre 1984) and are plotted as vectors in the Euclidean distance biplot. PCA-H analysis was performed using MATLAB as an operating platform and programs written by Dr. E.D. Gallagher of the University of Massachusetts, Boston.

MDS (Kruskal and Wish 1978, Kenkel and Orloci 1986, Clarke and Gorley 2006) also produces a two (or more)-dimensional map that demonstrates the relative distances between samples. This ordination technique is recommended over typical PCA procedures (other than PCA-H discussed above), since it is better at preserving sample distances and makes few assumptions about the nature of the data (Clarke and Gorley 2006).

4.3 Results and Discussion

4.3.1 Species Composition of 2007 Samples and Notes on Amphipods

In August 2007, 132 species of benthic infauna occurred in the samples, and for the period 1991–2007, 263 identified species have been recorded in the summer samples (Appendix D2). These results for the number of species are the same as reported for 2006, but the actual species recorded differ between the two years. Some species recorded in previous years were renamed or merged based on new taxonomic work (Maciolek *et al*. 2008). Four species, including *Listriella barnardi* and *Stenopleustes inermis* (amphipods), *Owenia fusiformis* (polychaete), and *Pusillina pseudoareolata* (gastropod) were newly reported in the harbor for the August samples.

Ampelisca spp. Two species of *Ampelisca* are found in Boston Harbor: *A. abdita* and *A. vadorum*; the former is associated with fine sand to muddy substrates, and the latter with coarse sand (Mills 1967). Early populations of *A. vadorum* have largely been replaced by *A. abdita*, which has accounted for nearly 97% of the *Ampelisca* identified since 1995. The two species have often co-occurred at T06 and T08. In the early years of the monitoring program, the taxonomic team did not discriminate between different species of *Ampelisca*; therefore both species are combined with juveniles and otherwise unidentifiable individuals to the taxon *Ampelisca* spp. for report purposes. Maciolek *et al.* (2004) investigated the effect of this “lumping” procedure on results obtained for diversity parameters, and concluded that there was no significant effect.

Because members of this genus are considered (by some) to be indicative of clean environments, population levels of *Ampelisca* have been considered key in following the status of the infaunal community of the harbor. Reish and Barnard (1979) found that slight increases in organic matter resulted in increased amphipod abundance, but beyond a certain level, amphipod numbers decreased. The possible relationship of *Ampelisca* abundances in Boston Harbor to carbon loading was examined in detail in Maciolek *et al*. (2008).

Ampelisca populations were almost entirely eliminated from the harbor in 2005 (Maciolek *et al*. 2006), following a major peak in numbers in 2003 (Figure 4-1). While increases in ampeliscid populations in the harbor through the 1990s have been partly explained as a response to cleaner sediments, the recent decline in numbers is most likely the result of severe storms in December 2003, December 2004, and May 2005, which affected the bottom substrate, altering the sediment texture (see Chapter 3 in Maciolek *et al.* 2006b) and bottom habitats. Although numbers of ampeliscid amphipods nearly doubled between 2006 and 2007, the totals are still less than half those recorded in 2002 and represent the fourth fewest number in the harbor since the monitoring program began (Figure 4-1). A shift from wastewater to phytoplankton-derived carbon, not all of which was available for the amphipods to directly utilize, may account for the slow recovery of amphipod populations (Maciolek *et al*. 2008).

Several other species of amphipods have been recorded at harbor stations (Table 4-1). In recent years, the large-bodied species *Leptocheirus pinguis* has been found in increasing numbers; in 2007 it was the most common amphipod species (Table 4-1), occurring primarily at T02 and T05A.

4.3.2 Benthic Community Analysis for 2007

Density, Species Richness, Diversity, and Evenness—Community parameters for the grab samples collected in 2007 at the nine harbor stations are shown in Figure 4-2 and Table 4-2. Data for 2006 are included in Figure 4-2 for comparison. As in previous years, trends in the parameters of interest differed at each of the stations.

Density—Total abundances in 2007 were significantly higher only at T05A where the amphipod *Leptocheirus pinguis* was very common; at the other stations, densities were generally similar to those in 2006 (T01, T07, C019), lower (T03, T04), or slightly higher (T02, T06, T08). Increases in density were usually due to higher numbers of amphipods at each station.

Species Richness —The mean number of species per sample was similar in 2007 to means recorded in 2006 at several stations (Figure 4-2), but was markedly higher at T05A (63.0±3.61 in 2007 vs. 41.0±2.0 in 2006) and T08 (66.0±8.7 in 2007 vs. 49.0±10.4 in 2006). As in all previous years, C019 and T04 had the lowest species richness of all harbor stations, with 8.7±1.5 species per sample at C019 and 9.3±1.2 at T04, a decline at both stations from means recorded in 2006 (Figure 4-2).

Diversity —Compared with 2006 values, mean Shannon diversity was generally the same or higher at all stations except C019 (Figure 4-2).Mean Shannon diversity was again lowest at CO19 (0.36±0.09) and highest at T08 (4.03±0.24) and T05A (4.06±0.10), a pattern similar to that recorded in previous years. Diversity as measured by Fisher's log-series *alpha* (Figure 4-2) increased at T05A and T07 compared with 2006 values, declined at T07; and was nearly identical at the remaining stations. Earlier station patterns were repeated in 2007: the lowest mean values were recorded at CO19 (1.45±0.39) and T04 (1.71±0.36) and the highest at T05A (10.58±0.82) and T08 (14.13±1.68).

Evenness—Evenness values in 2007 compared with 2006 were significantly lower at T02, T06, and T07; slightly lower or identical at T01, T03, T05A, T08, and C019 (Figure 4-2). The higher evenness at T02 reflects a change from a community highly dominated by *Nephtys cornuta* to one in which the distribution of individuals among species was more equitable.

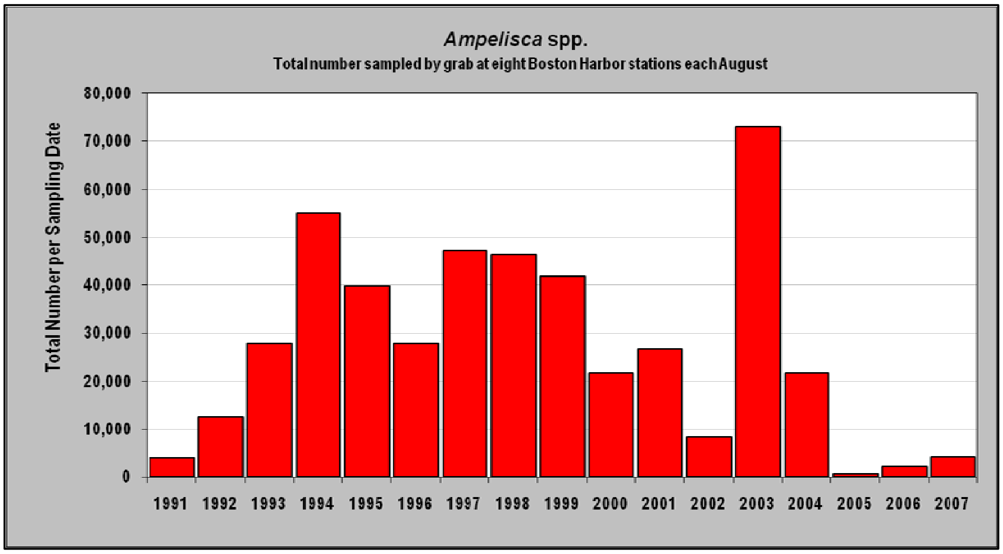

Figure 4-1. *Ampelisca* spp. at eight Boston Harbor stations.

Table 4-1. Total abundance of amphipod species in Boston Harbor grab samples 2003–2007.

Amphipod Species	2003	2004	2005	2006	2007
Ampelisca spp.	73,112	21,728	614	2,131	4,159
Leptocheirus pinguis	4,735	1,734	97	220	4,579
Unciola irrorata	3,841	756	18	93	2,004
Crassicorophium bonnelli	2,148	9	1	5	21
Photis pollex	2,108	1,677	100	219	196
Orchomenella minuta	1,194	1,230	21	54	1207
Dyopedos monacanthus	1,029	1		3	
Phoxocephalus holbolli	96	153		1	38
Microdeutopus anomalus	39	3	2		
Crassicorophium crassicorne	17	11		5	44
Ischyrocerus anguipes	9	2			1
Pontogeneia inermis	9	1			
Jassa marmorata	2	1			1
Harpinia propinqua	1				
Metopella angusta	1	3			3
Ameroculodes sp. 1				8	
Argissa hamatipes				6	
Monocorophium acherusicum				1	
Monocorophium inisdiosum				1	
Gammarus lawrencianus					6
Totals	88,341	27,309	853	2,747	12,259

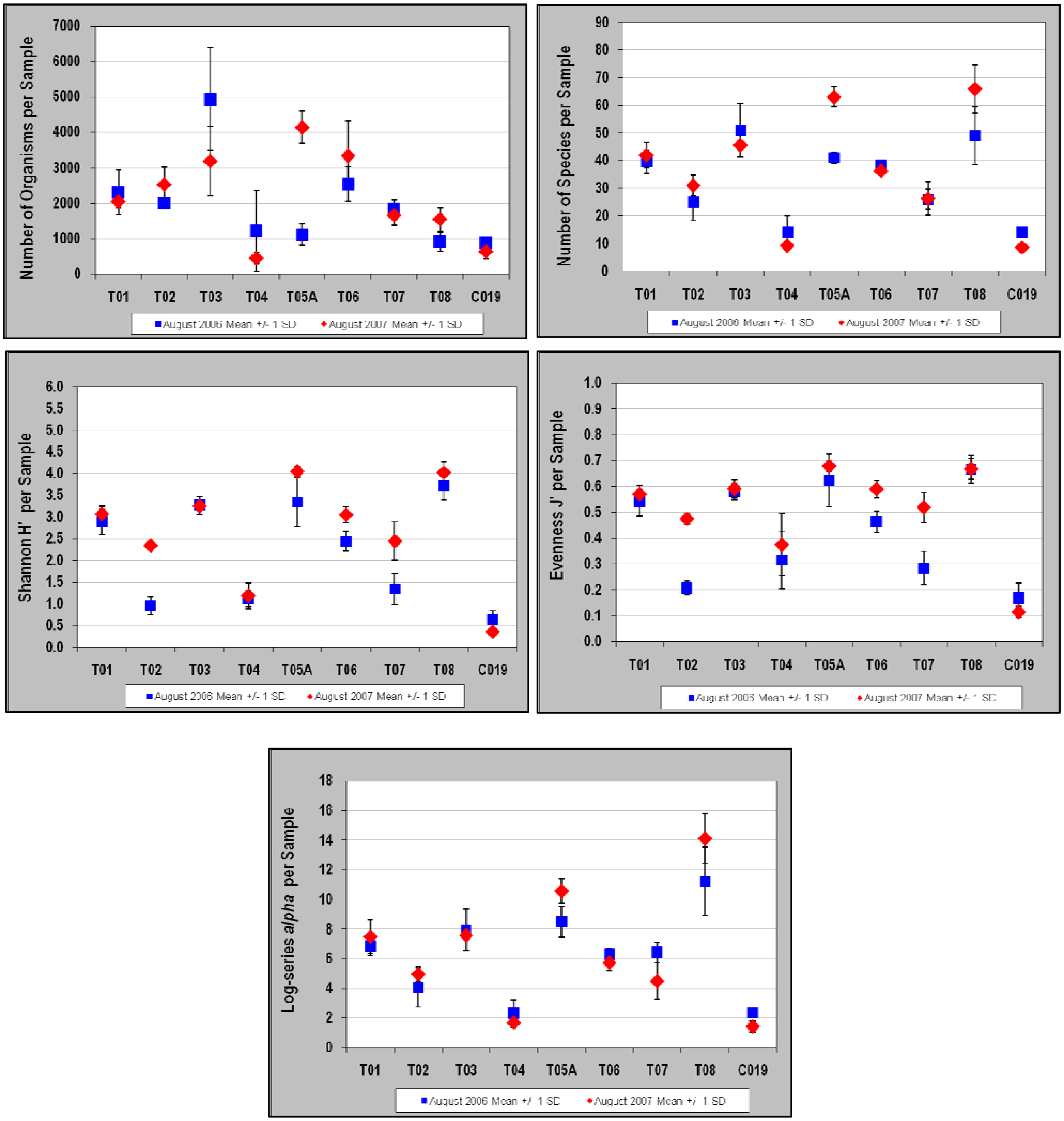

Figure 4-2. Mean ± 1SD of five benthic infaunal community parameters for the Boston Harbor stations sampled by grab in August 2007. The 2006 values are included for comparison.

Table 4-2. Benthic community parameters for samples taken at Boston Harbor traditional stations in August 2007.

Station	Replicate	Total Abundance	No. Species	H′ (base 2)	J′	Log-series *alpha*
T01	1	2175	41	2.98	0.56	7.17
	2	2128	38	2.97	0.57	6.57
	3	1858	47	3.27	0.59	8.77
	Mean ± SD	2053.7±171.1	42.0±4.58	3.07±0.17	0.57±0.02	7.51±1.13
T02	1	2093	28	2.34	0.49	4.57
	2	2454	30	2.39	0.49	4.81
	3	3041	35	2.32	0.45	5.55
	Mean ± SD	2529.3±478.5	31.0±3.61	2.35±0.04	0.48±0.02	4.98±
T03	1	2569	46	3.48	0.63	7.96
	2	4324	47	3.22	0.58	7.38
	3	2681	44	3.08	0.56	7.48
	Mean ± SD	3191.3±982.5	45.7±1.53	3.26±0.20	0.59±0.03	7.61±0.31
T04	1	591	8	1.54	0.51	1.31
	2	281	10	1.07	0.32	2.02
	3	483	10	0.96	0.29	1.79
	Mean ± SD	451.7±157.4	9.3±1.15	1.19±0.31	0.37±0.12	1.71±0.36
T05A	1	3726	62	4.17	0.70	10.58
	2	4618	60	3.97	0.67	9.76
	3	4088	67	4.03	0.66	11.40
	Mean ± SD	4144.0±448.6	63.0±3.61	4.06±0.10	0.68±0.02	10.58±0.82
T06	1	3966	35	2.99	0.58	5.29
	2	2226	37	3.27	0.63	6.31
	3	3848	37	2.92	0.56	5.68
	Mean ± SD	3346.7±972.3	36.3±1.15	3.06±0.18	0.59±0.03	5.76±0.52
T07	1	1360	27	2.41	0.51	4.80
	2	1913	20	2.02	0.47	3.12
	3	1720	32	2.91	0.58	5.60
	Mean ± SD	1664.3±280.7	26.3±6.03	2.45±0.45	0.52±0.06	4.50±1.27
T08	1	1615	71	3.84	0.62	15.27
	2	1849	71	4.30	0.70	14.93
	3	1196	56	3.97	0.68	12.20
	Mean ± SD	1553.3±330.8	66.0±8.66	4.03±0.24	0.67±0.04	14.13±1.68
CO19	1	454	10	0.38	0.12	1.81
	2	868	7	0.26	0.09	1.04
	3	593	9	0.43	0.14	1.51
	Mean ± SD	638.3±210.7	8.7±1.53	0.36±0.09	0.11±0.02	1.45±0.39

Dominant Species **—**The numerically dominant species and their percent contribution to the fauna at each harbor station in August 2007 are given in Appendix D3.

As discussed above, densities of *Ampelisca* spp. had increased in 2007 relative to 2006, but this taxon was not the top dominant at any of the harbor stations. It was most abundant at T03 and T08, ranking second at both stations, with mean densities of 543.7 and 302.0 individuals per sample, respectively, and accounting for 17% and 19% of the station fauna, respectively. The abundances at T03 represent a small decline in numbers relative to 2006, but those at T08 represent an order of magnitude increase. *Aricidea catherinae* remained the top numerical dominant at T03 and *Spiophanes bombyx* at T08. The amphipod *Leptocheirus pinguis* has been increasing in abundance at several harbor stations and was the top numerical dominant at T05A, where *Ampelisca* spp., a dominant in former years, ranked seventh. A large-bodied species, *L. pinguis* has been visible in the grab samples taken in the field. It has also been present in cores taken for the benthic flux program at BH02 (near T02) and BH08A (near T08) (Tucker, MBL, pers. comm. July 18, 2008). Examination of those cores by ENSR lab personnel revealed that *L. pinguis* appears to build a deep (ca. 5 cm) subsurface burrow with a short extension into the water; these tubes are not similar to those made by ampeliscid amphipods.

The polychaete species, *Nephtys cornuta*, a small jawed omnivorous polychaete, was once again a numerical dominant at several stations, although the overall density of this species declined in 2007 relative to 2006 (Figure 4-3, Table 4-3). It accounted for nearly 96% of the fauna at C019 and was the numerical dominant at T01 (ca.29 %), T04 (ca. 45%), T06 (ca.32%), and T07 (ca.48%). At all stations except T04 and C019, its abundance and proportion of the fauna declined compared with previous years. At T02, where *N. cornuta* had been the top numerical dominant since 2004, the polychaete *Polydora cornuta* and the amphipod *L. pinguis* ranked first and second in 2007. Overall, in 2007, *N. cornuta* accounted for 20.0% of the organisms collected at the infaunal harbor stations, compared with 37.8% in 2006. Examination of the gut contents of a few specimens of this polychaete revealed that it was consuming organic material, but no identifiable particles were noted.

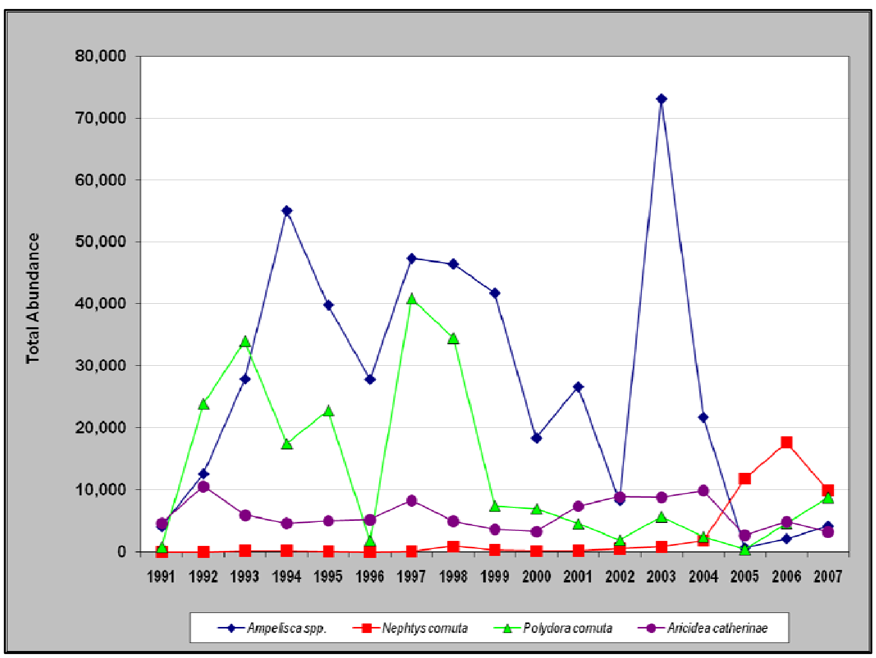

Figure 4-3. Total densities of four common species at eight Boston Harbor stations.

Table 4-3. Total annual abundance of *Nephtys cornuta* at eight stations in Boston Harbor.

Year	*Nephtys cornuta* (total individuals)	Year	*Nephtys cornuta* (total individuals)
1991	0	2000	188
1992	0	2001	215
1993	258	2002	573
1994	221	2003	910
1995	112	2004	1,838
1996	12	2005	11,825
1997	99	2006	17,670
1998	936	2007	9,911
1999	321		

Until 2007, the community at T04 had been dominated by *Streblospio benedicti* (72.0% of the fauna in 2006); however, in 2007, densities of *N. cornuta* were slightly higher than those of *S. benedicti*, making both species co-dominant and together accounting for over 88% of the total abundance at that station (Appendix D3). As in 2006, the distribution of *N. cornuta* in the three replicates was very uneven (352, 232, and 20 specimens, in replicates 1, 2, and 3, respectively), as was *S. benedicti* (166, 19, and 410, respectively). The remaining 12 species found at T04 accounted for only 0.07–5.76% of the fauna (Appendix D3).

C019 was originally sampled in 1989 as part of the Sediment-Water Exchange (SWEX) study (Gallagher and Keay 1998). At that time, 94–96 % of the fauna was comprised of *Streblospio benedicti* and a cirratulid identified as *Chaetozone setosa*; only a few individuals of four additional taxa were identified from the samples (oligochaetes, *Polydora* sp., *Mya arenaria*, and *Pectinaria gouldii*). *Mya arenaria* was found at this station in 2004 and 2005, but *P. gouldii* has not been recorded in the recent four years of sampling.

In 2007, as in the three preceding years, the fauna at C019 was overwhelmingly dominated by *Nephtys cornuta*, to an even greater extent than seen in previous years (96% in 2007 vs. ca. 90% in 2006), even though the absolute numbers were actually lower than in 2005 or 2006, as was overall total abundance (Figure 4-4). Species richness at this station dropped from the high of 24 species recorded in 2004 to 14 species recorded in 2007.

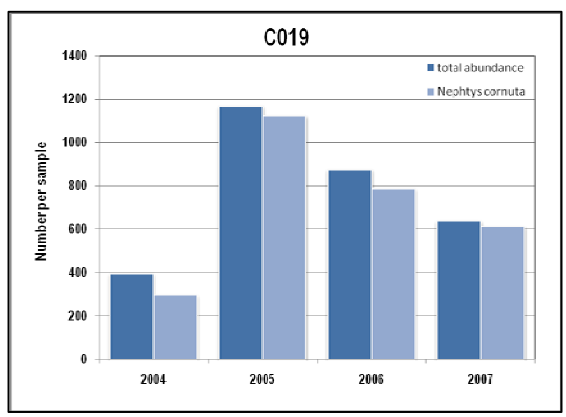

Figure 4-4. Total abundance and density of *Nephtys cornuta* at C019.

4.3.3 Multivariate Community Analysis of the 2007 Data

Similarity and Ordination Analysis with Bray-Curtis—The pattern of station similarity as elucidated by the Bray-Curtis algorithm after a square-root transformation of the data is similar if not identical to previously reported annual patterns based on both CNESS and Bray-Curtis with a fourth-root transformation of the data (Maciolek *et al*. 2006a,b; 2008) (Figure 4-5)

As in previous years, within-station similarity is very high, with all replicates from a station having highest similarity to other replicates from the same station and lower resemblance to samples from other stations. At the 50% similarity level, four groups can be identified:

Cluster 1. C019
Cluster 2. T04
Cluster 3. T01, T02, T03, T06, T07
Cluster 4. T05A and T08

with clusters 1 and 2 forming a larger group at ca. the 40% level, and clusters 3 and 4 being similar at about the same level. The harbor stations overall show a 20% level of similarity, indicating that several different habitats with differing community structures are present in the harbor.

Ordination of these samples by non-metric multidimensional scaling (MDS) is shown in Figure 4-6. The low stress level (0.08) of the 2-dimensional representation indicates that this sample map is a good representation of the multidimensional space occupied by the 27 samples, and indicates relative distances better than portrayed by the dendrogram. This representation confirms the pattern of the uniqueness of each harbor station, with wide separation between most of the stations (and even between some of the replicates from a station, as seen for T04). The 3-dimensional map (not shown) had a stress level of 0.05, indicating that the representation was excellent; this map showed that no station overlapped another in 3-D space.

The ANOSIM statistic was applied to test the null hypothesis that there is no significant difference between stations. The resultant statistic (global R) was R= 0.96 with a significance level of 0.1%. An R value of 1 indicates that all replicates within a site are more similar to each other than to any replicates from different sites. The result of this test suggests that there are significant differences among stations, but does not indicate which ones. Comparison of all station pairs except one resulted in R=1, indicating highly significant differences between stations (significance level = 10%). For the comparison of similarities between C019 and T04, R= 0.778, which was also significant at the 10% level. Thus, as was found for a similar analysis with the 2005 and 2006 data (Maciolek *et al*., 2006b 2008), each site within the harbor can be considered to be significantly different from the others.

The SIMPER routine was used to determine which species contributed the most to the differences between stations, and also to differences between the four major clusters (see Figure 4-5), and between the two major clusters (C019 and T04 vs. all other stations). Gallagher's PCAH routine was used to confirm the results obtained with SIMPER. Both analyses suggested that *N. cornuta* and *S. benedicti* structured C019 and T04, and that although *N. cornuta* was common at some of the remaining stations, the species accounting for differences among stations were the oligochaete *L. medioporus* and the amphipods *L. pinguis*, *O. minuta*, and *Ampelisca* spp. Details are presented in Appendix D4.

Figure 4-5. Cluster dendrogram of the 27 samples collected in 2007 at nine Boston Harbor stations. The analysis is based on a square-root transformation of the data, Bray-Curtis similarity, and group average sorting. Dotted line indicates 50% similarity.

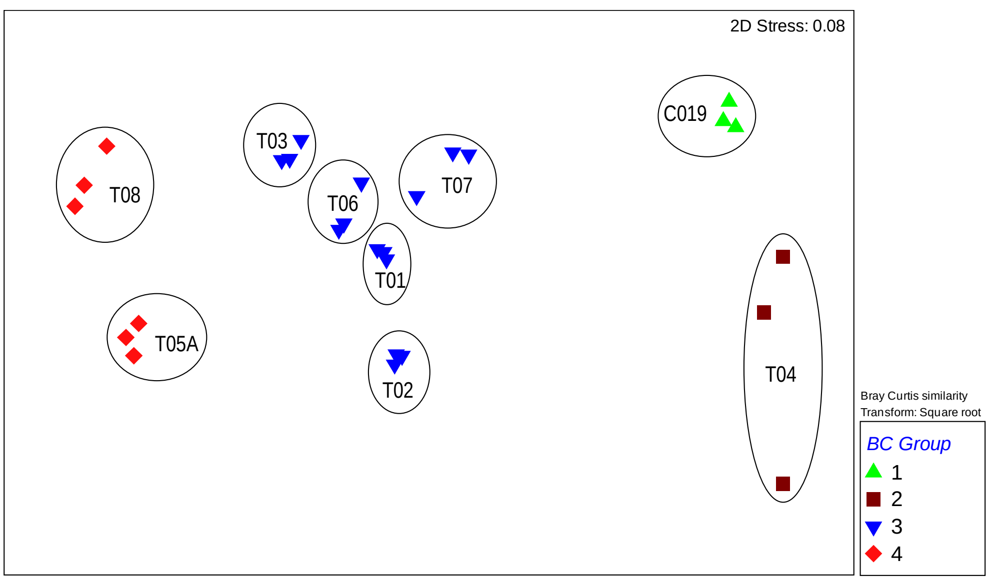

Figure 4-6. MDS diagram of the 2007 clusters, derived from the similarity matrix based on a square-root transformation of the data, Bray-Curtis similarity, and group average sorting.

4.3.4 Long-term Monitoring (1991–2007): Annual Harborwide Changes

Monitoring at eight harbor stations has now continued for 17 years, during which time the pollutant load to the harbor has been significantly reduced. Additionally, severe weather events, including spring and winter nor'easters and heavy rainfalls have impacted the harbor. These physical factors are integrated by the benthic populations, and, combined with the natural expansion and reduction of biological populations, have resulted in the community patterns that have been recorded to date.

Parameters calculated for each replicate and then averaged for each year are shown in Figure 4-7. In general, all parameters except abundance trended upward through 2004, when the harbor was affected by major storms that (at least partly) accounted for the loss of the dense populations of ampeliscid amphipods. The mats formed by these amphipods provided substrate and microhabitats that supported diverse benthic populations. With the loss of the amphipods and these habitats, all diversity parameters showed a significant decline in 2005 and 2006 when compared with previous years. Although the ampeliscids have not returned to the harbor in mat densities, the univariate measures of diversity showed an increase in 2007 compared with the previous two years.

The Shannon diversity index H′ has ranged from a low of 2.09 in 1991 to a high of 3.00 in 2004 (Figure 4-7), with the 2007 value of 2.93 being the third highest of the 17 years. Although the SE around each mean suggests that these values may not all be significantly different from each other, mean values were generally higher in years after the outfall diversion (2000) compared with earlier ones, suggesting higher species diversity after the diversion. Mean H′ for the eight years prior to outfall diversion (1993–2000; 1991 and 1992 are not considered here because T05A was not sampled) was 2.50±0.22SD, compared with 2.75±0.23SD for the seven years since outfall diversion. The associated evenness index, J′, was lower in the early years of monitoring, indicating higher dominance by fewer species during those years (Figure 4-7); J′ was also low in 2005–2006, when *Nephtys cornuta* dominated the fauna at several stations.

The average number of species per sample, the most direct measure of species richness, ranged from 18.3 in 1991 to 51.0 in 2003, with a subsequent drop to 34.0 in 2005 (Figure 4-7). This value rose over the next two years to 40.0 in 2007. The eight years prior to outfall diversion had a mean of 34.0±3.5SD species per sample, whereas the seven post-diversion years have a mean of 39.5±5.6SD species per sample.

Log-series *alpha* exhibited the strongest upward trend over time, from low values in the early 1990s to higher values in recent years, with 2003 and 2004 in particular having higher mean values than in all previous years (Figure 4-7). The subsequent drop in 2005 was not reversed in 2006, when the mean value (6.43) was only slightly higher than that recorded in 1998 (6.31); however, *alpha* in 2007 was 7.10, the third highest value recorded in 17 years. When the eight years pre- and seven years post-diversion were considered, mean alpha rose from 5.60±0.42SD to 7.20±0.73.

In order to examine the overall change in harbor benthic communities, samples were pooled to one sample per year (*i.e.*, all samples from all stations were pooled to one annual harbor-wide sample, resulting in 16 harbor samples) to examine harbor-wide averages (see Methods). Pooling across stations is probably not entirely valid because of the wide differences among stations in terms of sediment type and environmental conditions (*e.g.*, water circulation patterns, depth, etc.). However, because differences were seen at individual stations, both in terms of infaunal community structure, SPI, and sediment characteristics, averaged annual differences were investigated in order to determine if there were any apparent annual patterns as well. As discussed below, some analyses were more informative than others.

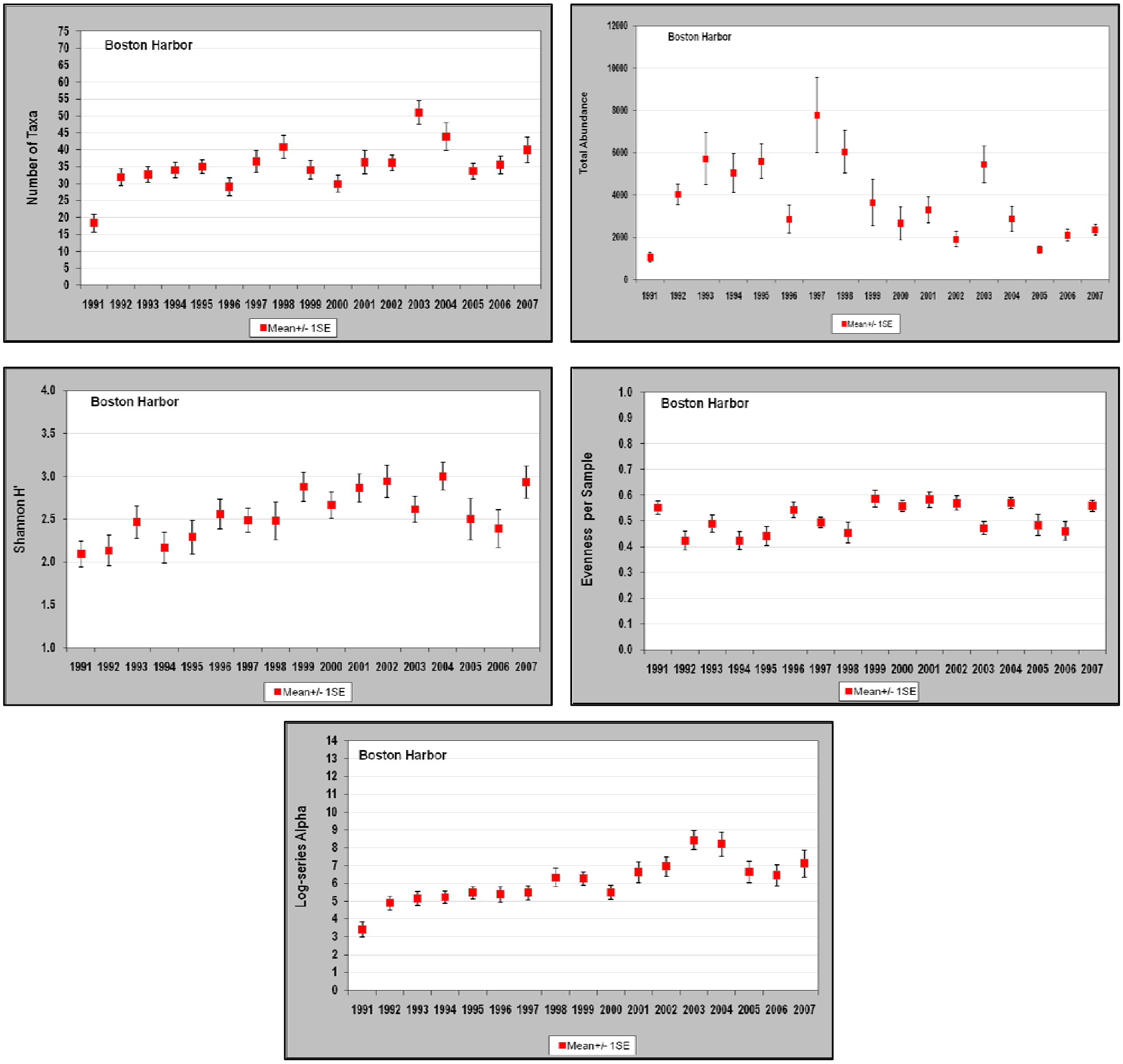

Figure 4-7. Benthic community parameters for Boston Harbor stations for each August (or September) sampling event from 1991–2007.

Rarefaction Analysis— Rarefaction analysis is essentially a measure of species richness, with loss of information about the relative abundances of each species (Magurran 1988). However, it is useful as a way to compare the overall diversity in the harbor for each year of the sampling program. The results indicate an increase in diversity since the early 1990s and especially after 2000, when the discharge was diverted offshore (Figure 4-8). The curve for 2004 is the highest reported to date; diversity as measured by this method was similar in 2007 to results for 2005 and 2006.

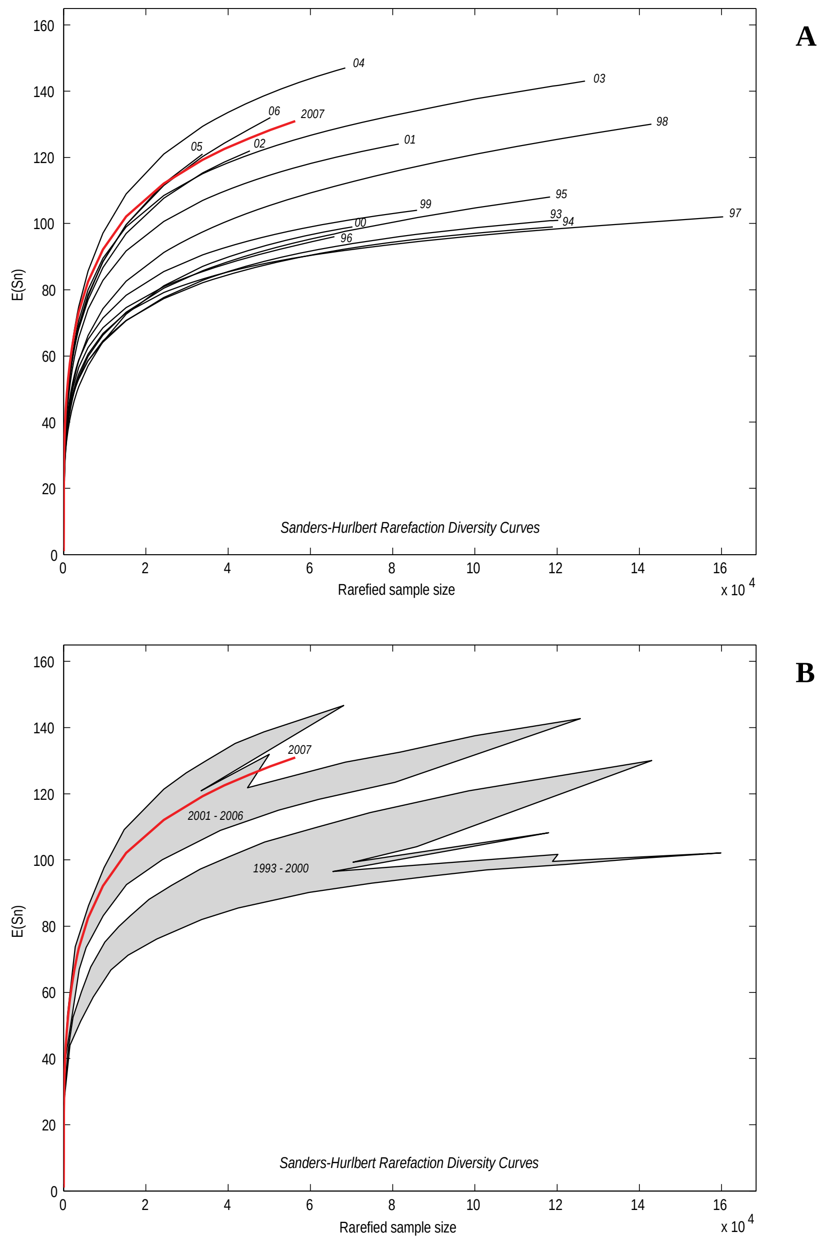

Figure 4-8. (A) Rarefaction curves for August samples taken in Boston Harbor each year from 1993 through 2007, (B) Range of curves for pre- and post-diversion years. All samples pooled within each year.

Similarity and Ordination Analysis with CNESS—Based on the CNESS similarity analysis, three major groups or clusters of annual samples were identified at a CNESS level of 0.60 (Figure 4-8). This dendrogram is nearly identical to that presented for data through 2006 (Maciolek *et al.* 2008), but because 1991 and 1992 were eliminated from this analysis, the years included in cluster group 1 differ slightly from previous reports. Cluster group 1 includes years 1993–1998 (except 1996), group 2 comprises 1996 plus 1999–2004, and group 3, which includes 2005–2007, has the lowest similarity to the remaining years (Figure 4-8), possibly because of the high numbers of *Nephtys cornuta* in the samples. Similarly, 1998 was distinguished by a large number of *Capitella capitata* complex at T04, possibly accounting for the dissimilarity of that year to others in cluster group 1.

The metric scaling of these 15 (1993–2007) annual samples on the first two PCA-H axes accounted for 58% of the CNESS variation (Appendix D4). The contribution of species to the PCA-H axes indicated that once again, the polychaete *Nephtys cornuta* had the largest influence on the metric scaling of the annual samples, with a contribution of 14% (compared to 7% in 2005 and 11% in 2006) (Maciolek *et al*. 2008). *Nephtys cornuta* and an additional nine species (*Tubificoides apectinatus, Crassicorophium bonelli, Streblospio benedicti, Phoxocephalus holbolli, Polydora cornuta, Leptocheirus pinguis, Ampelisca* spp.*, and Capitella capitata* complex) together accounted for 70% of the total variation.

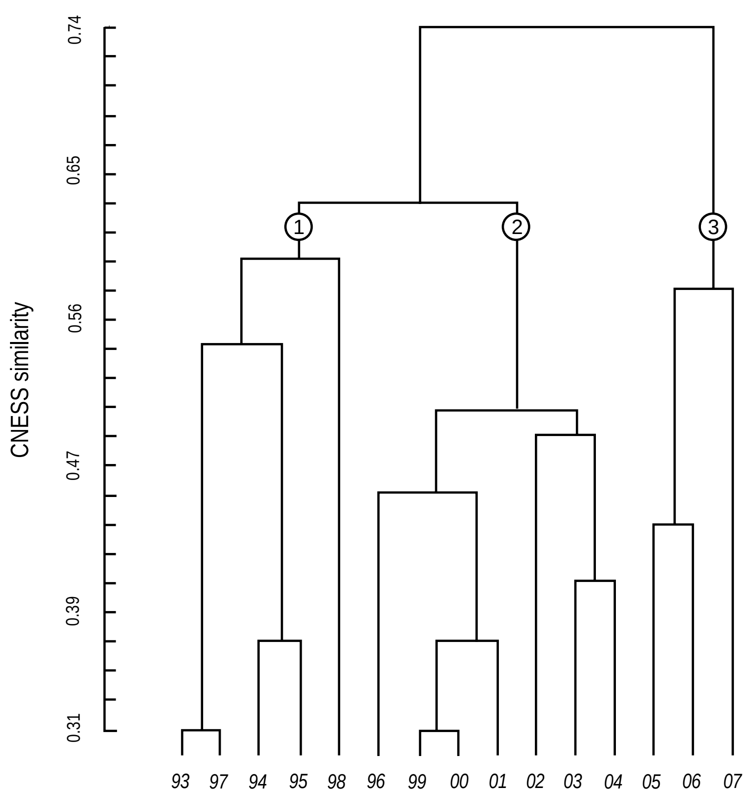

Figure 4-8. Cluster diagram for Boston Harbor 1993–2007 infauna. The lower the CNESS number, the more similar the years. CNESS *m* = 20 and group average sorting were used. 258 taxa and 15 pooled annual samples were included.

Similarity and Ordination Analysis with Bray-Curtis**—**The Bray-Curtis similarity analysis based on a square-root transformation of the data returned results (Figure 4-9) that at first appear somewhat different than with CNESS but on closer inspection show the same general patterns of station similarity, strongly suggesting a dichotomy between the years prior to moving the outfall offshore and those after the move.

When the data were square-root-transformed prior to analysis, the abundant species such as *Nephtys cornuta* and *Polydora cornuta* were down-weighted (but less severely so than with the fourth-root transformation used last year; see Maciolek *et al.* 2008). In previous years, three groups were evident, with 1991 forming a highly dissimilar outlying group; because that year was not included in the current analysis, that group is not present. Two major clusters of samples are evident, 1992–2001 forming one major group and 2002–2007 forming a second group. With CNESS (Figure 4-8), a group comprised of samples from 2005–2007 comprised a third, dissimilar group, whereas with Bray-Curtis, those samples have a high similarity to those from 2002–2004 and together form the second major cluster. Both algorithms indicate a group comprised of 1993–1998 (except 1996) as well as a separate cluster comprised of 1996 plus 1999–2001.

Ordination of these samples by non-metric multidimensional scaling (MDS) is shown in Figure 4-10. The low stress level (0.07) indicates that this sample map is a good representation of the multidimensional space occupied by the annual samples.

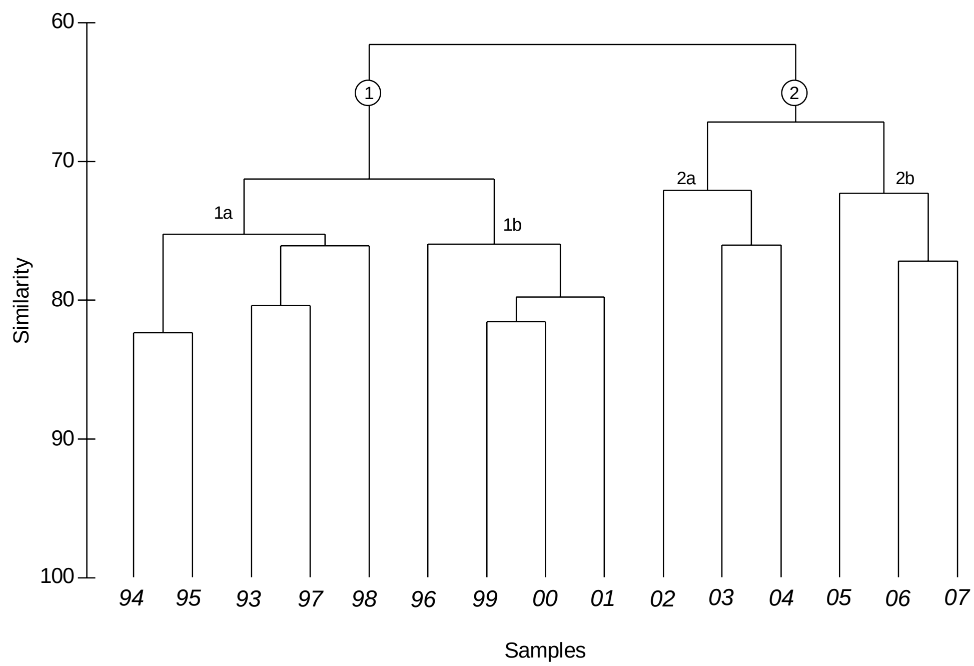

Figure 4-9. Cluster dendrogram based on the Bray-Curtis similarity analysis of Boston Harbor 1993–2007 infaunal data, after square-root-transformation of the data and group average clustering.

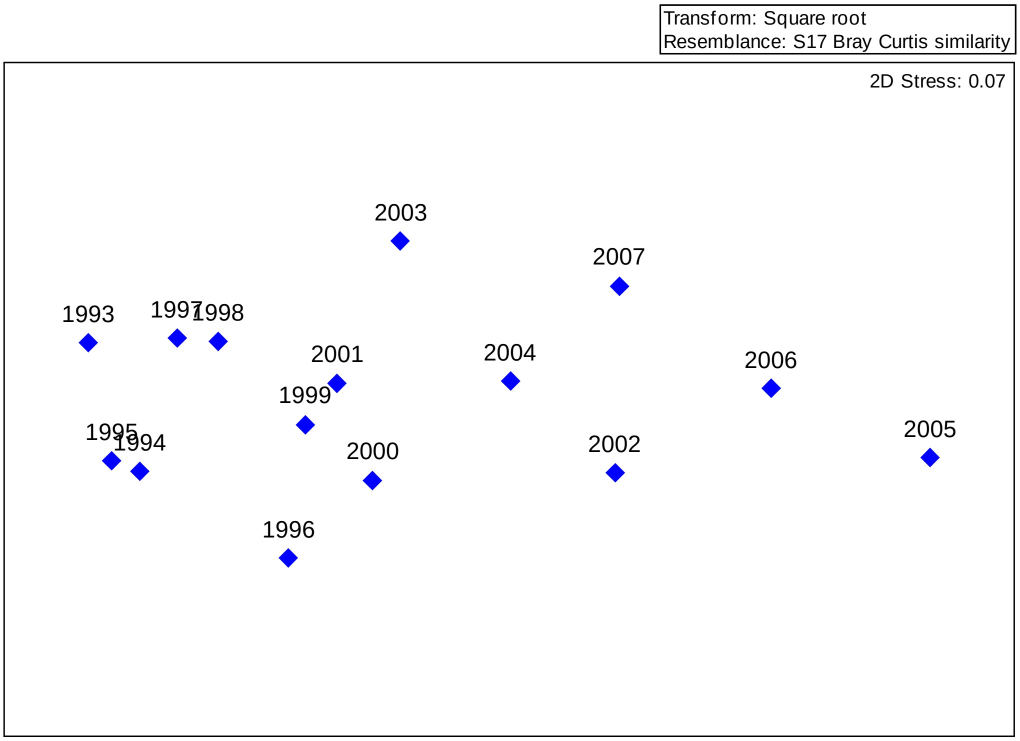

Figure 4-10. MDS based on the Bray-Curtis similarity analysis of Boston Harbor 1993–2007 infaunal data, after a square-root-transformation of the data.

A SIMPER (similarity percentages) analysis of the 1992–2007 annual samples (Appendix D4) indicated that abundances of *Ampelisca* spp. was the taxon most responsible for the similarity of samples in the Bray-Curtis cluster Group 1 (1993–2001) with a contribution of 15.2% to the within-group similarity. *Polydora cornuta*, *Limnodriloides medioporus*, and *Aricidea catherinae* also typified that cluster, but with successively less contribution to the within-group similarity. In contrast, Group 2 (2002–2007) was characterized by *Tubificoides apectinatus*, *Aricidea catherinae*, *Limnodriloides medioporus*, *Ampelisca* spp., *Nephtys cornuta*, and *Polydora cornuta*, with contributions ranging from 7.9% to 3.1% to the overall within-group similarity (Appendix D4).

The analysis also reveals the species responsible for the dissimilarity between groups 1 and 2, which more or less equate to before and after the discharge, was moved offshore (Appendix D4). In this case, *Ampelisca* spp. is the taxon contributing the most (10.3%) to the discrimination between the two cluster groups. *Polydora cornuta* (6.7%) and *Nephtys cornuta* (5.6%) are also important in defining the differences.

Although the PCA-H and SIMPER analyses are different approaches to the problem, both suggest a similar suite of species as important in both typifying the major groups of years and discriminating between them.

4.3.5 Long-term Changes in the Infaunal Communities

Early studies—Benthic communities in Boston Harbor were clearly impacted by decades of pollutant discharge. The early studies of benthic communities in Boston Harbor (1978, 1979, and 1982) indicated distinct groupings of stations that corresponded to (1) a progression from higher saline oceanic conditions in the outer harbor to estuarine conditions in the inner harbor and (2) known areas of pollution (Blake and Maciolek 1990, Maciolek *et al*. 2004). A distinct outer harbor assemblage that included species with close affinities to faunal communities in Massachusetts Bay changed in the middle of the harbor to one that included estuarine species and elements of so-called pollution indicators or stress-tolerant taxa.

All stations in the outer harbor assemblage had more species and higher species diversity values regardless of differences in sample size or analytical technique. Stations having high infaunal densities were found throughout the station array, but opportunistic species such as *Streblospio benedicti* were found only at the stations in the middle of the harbor. The early data also clearly indicated an obvious north/south pattern in the benthic communities, with stations near the northern Deer Island outfall being distinctly different from those near Nut Island in Hingham Bay in the southern part of the harbor. Tidal exchange through President Roads and Broad Sound appeared to be sufficient to maintain benthic assemblages that were only moderately stressed despite their proximity to the sewage and sludge outfalls. In contrast, shallow sites to the east and west of the outfall had low diversities and high densities of opportunistic stress-tolerant species.

Pollution abatement and sediment characteristics—Discharge of sludge into the harbor ended in 1991 and in 1998 all effluent discharge from Nut Island was discontinued and full secondary treatment of the effluent was implemented. On September 6, 2000, all wastewater discharges were diverted to the new outfall in Massachusetts Bay, and in early 2001, the final battery of secondary treatment became operational. Taylor (2005, 2006) summarized the major patterns in freshwater flows and loadings of total nitrogen (TN), total phosphorus (TP), total suspended solids (TSS), and particulate organic carbon (POC) to Boston Harbor between 1995 and 2003. He elucidated four periods, as outlined in Chapter 1(this report) and discussed in relation to the SPI results (Chapter 3, this report.) The changes in wastewater discharge from 1991 to 2005 resulted in an 80–95% decrease in loadings to Boston Harbor. Annual average loadings of TSS and POC showed a progressive decrease, starting in 1991/1992 and proceeding through 2001, after which the average loadings remained low and similar between years. For TN and TP, loadings showed some decrease with the end of sludge discharge, but remained elevated through 1998, when Nut Island flows were discharged closer to the mouth of the harbor, resulting in decreased inputs to the harbor. TN and TP showed additional, larger decreases with the transfer of the effluent discharge offshore in 2000 (Taylor 2006).

TOC content has decreased significantly over the monitoring period at northern stations T01 and T03, and also at T08 when data from 1991 is included in the analysis. These findings suggest a reduction in carbon loading (especially to the northern harbor) consistent with the improvements to wastewater treatment practices. Decreasing trends in TOC content were also apparent at stations T05A, T06, and T07, although the decrease was not significant, possibly because of the high variability among the data. Significant changes in TOC over time have not been evident at stations CO19, T02, or T04 (Appendix B, this report).

Abundances of *Clostridium perfringens* have decreased significantly over the monitoring period at five of the harbor stations (T01, T02, T05A, T06, and T08), although abundances increased (0.2 to 10-fold increase) at all harbor stations in 2007 compared with 2006 values (Appendix B, this report). At most harbor stations, however, the 2007 abundances were less than average values measured over the entire monitoring period. The 2007 increase may reflect natural variability, redistribution of surface sediments, or inputs to the system.

Harbor stations include locations with dissimilar grain-size characteristics: T01, T05A, and T08 generally have coarse-grained sediments; T04 and CO19 have fine-grained (silty) sediment; and T02, T03, T06, and T07 have been comprised of sediments with roughly equal parts coarse- and fine-grained material (Appendix B, this report). Grain-size composition has changed significantly over time (1991–2007) at stations T02, T04, and T07, as evidenced by a significant increase in percent fines, but other temporal changes in sediment environments at some harbor stations have been difficult to discern because of the high variability among the data over time.

Recovery of benthic communities—Recovery of areas degraded by the long-term disposal of sludge and effluents may involve a transitional stage of undetermined length before an equilibrium community is established. This intermediate stage can involve the sequential appearance and decline of a diverse assemblage of tube-dwelling amphipods, mollusks, and polychaetes. *Ampelisca* spp. can thrive in areas within a certain range of organic input and good water quality (Stickney and Stringer 1957). Beginning in 1993, the *Ampelisca* spp. population in the harbor spread and in 2003 the populations of this and other species of amphipods accounted for 75 % of the sampled fauna, the second highest density since 1998. In 2004, the amphipod populations had declined and by 2005 this major faunal component, which had dominated much of the harbor benthos over the 15 years of this study, was almost entirely absent. The reduction in *Ampelisca* spp. and high-density tube mats may be related to depletion of the organic matter stored in the sediment, as well as to the impact of the severe storms in recent winters. While the total annual carbon budget for Boston Harbor should be sufficient to support high densities of *Ampelisca* in any one year, a shift from wastewater- to phytoplankton-derived carbon, all of which may not have been available to the amphipods, may have resulted in the apparently slow recovery of this species in 2006 (Diaz *et al*.2008).

With the major decline in amphipod populations, the population of the small polychaete *Nephtys cornuta* irrupted at several stations throughout the harbor and has dominated benthic communities for the past three years (2005–2007). On the east coast of the US, this polychaete was described from a shallow water location in Maine (as *Aglaophamus neotenus*) by Noyes (1980); Hilbig (1994) synonymized the species with *Nephtys cornuta*, a common species on the west coast (*i.e*., California to British Columbia and Alaska). Noyes (1980) found *N. cornuta* in sediments that were mixtures of fine silt, clay, and sand grains; these sediments also had large amounts of organic material. Similarly, it has been reported in several west coast studies as an opportunist, found in high numbers in areas recovering from, for example, salmon farming, where the organic load may be high (Brooks *et al*. 2004). Noyes examined fecal pellets produced by freshly collected specimens of *N. cornuta*; he classified it as a nonselective omnivore after determining that it fed on benthic diatoms, copepods, and unidentified organic material. Recent evidence from SPI that the harbor sediments contain large numbers of diatoms, plus the organic material released from disintegrating tube mats, probably fueled the population explosion of this species.

Mean community parameters for the harbor overall were summarized for discharge periods (Taylor 2006) offset by one year to allow for any lag time in the response of benthic populations to decreased pollutant loads (Table 4-4). Periods II and III appear the most similar for all parameters. Fisher's *alpha* shows a steady increase through all time periods, whereas the mean values of other parameters appear identical or decline between subsequent periods (*e.g*., number of species, periods II and III; Shannon diversity, periods III and IV).

Table 4-4. Characteristics of Boston Harbor traditional stations summarized by discharge time periods defined by Taylor (2006).

Parameter	Period			
	I before Dec. 1991	**II** Dec 1991–mid-1998	**III** mid-1998–Sep. 2000	**IV** after Sep. 2000 *(after outfall diversion)*
Groupings offset by one year	***n*= 48 (1991–1992)**	***n* = 144 (1993–1998)**	***n*= 70 (1999–2001)**	***n* = 144 (2002–2007)**
Number of Species	25.1 ± 14.25	34.7 ± 13.6	33.5 ±14.2	40.0 ± 16.6
H′	2.11 ± 0.81	2.41 ± 0.90	2.80 ±0.78	2.73 ± 0.97
log-series *alpha*	4.14 ± 2.13	5.50 ± 2.00	6.13 ± 2.24	7.29 ± 3.09
Rarefaction curves	1991 Lowest	Low	Intermediate	Highest
Fauna	highest abundances of opportunistic species such as *Streblospio benedicti* and *Polydora cornuta*	declining abundances of opportunistic species, some amphipod species numerous	fewer opportunists, more oligochaetes, some amphipod species numerous	some species from Massachusetts Bay, rise and decline of amphipods, irruption of opportunistic polychaete *Nephtys cornuta*

Given the physical and oceanographic attributes of the study area (*i.e.*, a near-coastal environment that is relatively shallow compared with offshore areas, and a continuing pollutant load, albeit reduced, from CSOs or other industrial sources), it is probable that the harbor benthos will continue to evidence episodic irruptions and declines of populations of amphipods and other species as has been documented over the past several years. Even so, the concomitant decrease in carbon loading and levels of *Clostridium perfringens*, plus increase in community parameters such as species richness and Fisher's *alpha* at several locations in the harbor, point towards a cleaner benthic environment.

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